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Cognitive control processes and their neural bases in bilingualism

Les processus de contrôle cognitif et leurs bases neuronales dans le bilinguisme

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en Psychologie

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ABSTRACT

The present doctoral thesis aimed to study the relation between bilingualism and domain-general executive control. Psycholinguistic research on bilingualism has shown that the sustained co-activation of languages and the need to adapt to the linguistic environment lead to a reinforcement of control abilities in bilinguals. However, the nature of domain-general executive control involvement in multiple language use is a matter of debate. Three studies were conducted in order to investigate this issue at the neuronal level in French-German late bilinguals. Different experimental tasks involving a cognitive conflict were used, certain of them involving a linguistic component (Stroop and negative priming) and the other one involving a motoric component (antisaccade). The main findings collected in the present doctoral thesis showed (1) the behavioral and neurophysiological evidence of enhanced conflict monitoring and inhibition in bilinguals, (2) the more efficient dynamic interplay between anterior cingulate cortex and the prefrontal cortex in executive control in bilinguals in comparison with monolinguals, and (3) a modulation of the executive control by the individual linguistic factors inherent to bilingualism. Taken together, the present findings support psycholinguistic theories postulating domain-general control involvement in bilingualism and reveal the capacity of neuroplastic adaptation as a function of linguistic constraints.

Keywords: bilingualism, language control, domain-general executive control, conflict monitoring, inhibition, neuroplasticity, Stroop task, negative priming, antisaccade task, electroencephalography

RESUME

L’objectif de la présente thèse de doctorat était d’étudier la relation entre le bilinguisme et le contrôle exécutif général. Les recherches sur le bilinguisme en psycholinguistique ont montré que la co-activation permanente des langues ainsi que la nécessité de s’adapter à l’environnement linguistique peuvent produire un renforcement des capacités de contrôle chez les bilingues. Toutefois, la nature des processus de contrôle impliqués reste controversée. Trois études ont examiné cette question au niveau neuronal chez des bilingues tardifs français-allemand. Différentes tâches expérimentales mettant en jeu un conflit cognitif ont été utilisées, les unes impliquant une composante linguistique (Stroop et amorçage négatif), et une autre impliquant une composante motrice (antisaccades). Les principaux résultats sont les suivants : (1) Renforcement des processus de gestion de conflits et d’inhibition chez les bilingues, (2) Interaction entre le cortex cingulaire antérieur et le cortex préfrontal dans le contrôle cognitif plus efficace chez les bilingues que chez les monolingues et (3) Modulation du contrôle exécutif par divers facteurs linguistiques individuels inhérents au bilinguisme. Prises dans leur ensemble, ces observations corroborent l’hypothèse d’une implication de processus de contrôle général dans le bilinguisme et révèlent des capacités d’adaptation neuroplastique en fonction des contraintes linguistiques.

Mots-clés : bilinguisme, contrôle des langues, contrôle exécutif général, gestion de conflits, inhibition, plasticité neuronale, tâche Stroop, amorçage négatif, tâche antisaccades, électroencéphalographie

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SUMMARY

The present doctoral thesis investigated the relation between bilingualism and executive control processes. In psycholinguistics, it is now widely accepted that bilingual individuals present a sustained co-activation of their two languages, even if a given linguistic context requires the use of only one specific language (non-selective language access; Brysbaert, 2003; Dijkstra, 2005; Hoshino & Thierry, 2011; Van Heuven et al., 1998). As a direct consequence of the co-activation of multiple languages, control processes are required in order to successfully control cross-language interferences (Blumenfeld & Marian, 2013; Costa, Albareda, & Santesteban, 2008; Runnqvist, Strijkers, Alario, & Costa, 2012), and to adapt the use of languages to a given linguistic and environmental context (Green & Abutalebi, 2013). This particular situation of language use is assumed to lead to a *reinforcement* of specific control processes in order to meet communicative requirements in both languages. Indeed, one of the most challenging tasks of a language system managing two co-activated languages is to maintain an efficient communication between interlocutors. Critically, it needs to refrain the possible grammatical negative transfers (i.e. interferences) between the two simultaneously activated linguistic systems (but often at different levels of activation), in particular from the most automatized language, i.e. in general the mother tongue, toward the less automatized one, in general the second language. Still on the issue of bilingual language processing, another assumption is that some of the hypothesized control processes may be shared by different domains, i.e. the so-called *domain-general* executive control processes. However, to date, caution is at order before drawing firm conclusions regarding the exact relation between the regular use of a second language and the efficiency of cognitive control processes. Indeed, not only a robust bilingualism benefit in executive control remains disputable but also the nature of the domain-general executive control processes assumed to be involved in multiple language use is a matter of debate. The main goal of the current work was to test whether the neurodynamics of different domain-general executive control processes, i.e. conflict monitoring,

interference suppression, response inhibition, overcoming of inhibition, among others, thought to be involved in monolingual as well as in bilingual language processing vary across these two groups of individuals. Our main hypothesis was that a bilingualism advantage should be reflected by an enhancement of the efficiency of control in bilinguals at both the behavioral and neurophysiological levels; this should be mirrored on the ERP signatures thought to be associated with each of the control processes studied here. Another question addressed in the doctoral thesis was how these different control processes are related and influence each other. It has been argued that the processing of a second language (L2) involves the same cerebral areas as those for processing the first language (L1) independently of the age of acquisition of the L2 (Abutalebi, 2008). However, in addition to the activation of the language areas, learning and use of a second language requires the participation of brain areas known for their role in cognitive control, for avoiding, as already indicated, cross-language interferences. The involvement of domain-general cognitive control mechanisms in bilingualism is thought to reflect the necessity to control interferences that the dominant and highly automatized language may exert on a less automatized language, in general the L2 (Abutalebi, 2008). Even if the implication of executive functions in bilingual language processing has been intensively explored in behavioral and neuroimaging studies, many questions remain to be elucidated, especially concerning the exact nature of the involved control processes. Despite the abundant literature, the absence of consensus still observed in this domain of research may in part be explainable by the diversity of bilingualism especially in terms of typology of languages and of individual differences both intrinsic but also for grammatical knowledge.

Different neurocognitive models of language processing have discussed the implication of domain-general executive control processes in language processing, e.g. Fedorenko and Thompson-Schill (2014), or the *Memory Unification Control* (MUC) model proposed by Hagoort (2005, 2014). In the MUC model, Hagoort postulates that Broca’s area (i.e. the inferior frontal cortex, BA 44 and BA

45) is not necessarily a region specific to language processing but might also have the function of language unification (*binding*) due to its connections with language-specific areas in the temporal and inferior parietal cortex. Moreover, according to the MUC model, control processes are reflected by activation in the prefrontal cortex (PFC) and the anterior cingulate cortex (ACC), amongst others (Hagoort, 2005, 2014). Similarly, Fedorenko and Thompson-Schill (2014) assume that in L1 language processing the neuronal underpinnings of domain-general executive control may involve prefrontal, inferior frontal and parietal regions. Moreover, beyond monolingual language use, individuals mastering more than one language are experiencing specific control demands that moreover are increased (Blumenfeld & Marian, 2013). Regarding the neurocognitive modeling of language control in bilingualism, amongst the most influential models, some of them postulate that there is a non-selective language access: (1) the *Adaptive Control Hypothesis* (Green & Abutalebi, 2013) - preceded by the *Inhibitory Control Model* (Green, 1998), (2) the *Bilingual Interactive Activation+* (BIA+) model (Dijkstra & van Heuven, 2002; Van Heuven et al., 1998), (3) the model of lexical access proposed by Costa, Miozzo and Caramazza (1999) / Costa (2005), (4) the neurobiological framework of how bilingual experience improves executive function by Stocco, Yamasaki, Natalenko and Prat (2014). The IC model involves multiple levels of control, which exert their regulatory function via both, external (bottom-up/exogenous) and internal (top-down/endogenous) control. One assumption of the IC model (Green, 1998), i.e. a production model, is that in realizing communicative actions, task schemas (i.e. thought to be mental devices or cognitive networks that individuals may construct or adapt in real time in order to achieve a specific linguistic task, such as producing a word) play a central role. The rationale is that when a specific language task, for example to produce a word in French (and not in Mandarin Chinese), has to be realized, a specific network, i.e. a so-called language task schema in the terminology of Green, among different networks will be activated and non-target task schemas will be inhibited via top-down control in order to execute this specific linguistic task. Each specific language task has to activate specific linguistic elements and to suppress by means of a top-down mechanism of

control all elements, which are irrelevant and therefore are considered as competitors for this task. It is important to note that task schemas are required in both, mono- and bilingual language use, but in bilingualism there is the additional requirement that a target language needs to be selected for achieving a specific linguistic goal and any non-target language needs to be suppressed. The selection or inhibition of a language is carried out via language *tags*. The revisited version of the IC model, i.e. the *Adaptive Control Hypothesis* (Green & Abutalebi, 2013) also postulates that domain-general executive control processes are involved in language control. It is supposed that bilinguals regularly using a foreign language require their control processes in general more intensely than individuals using less regularly a foreign language (i.e. the so-called *monolinguals*). Consequently, one may think that bilingualism presents a training effect on domain-general cognitive control. Depending on the interactional (language) context, which is defined by the frequency and pattern of language switching or language separation (e.g. *single language contexts* in which only one language is of use in a given context, *dual language contexts* in which two languages are used but in strict separation and with different interlocutors, and *dense code-switching contexts* in which languages are mixed even within single utterances; Green & Abutalebi, 2013), certain among the domain-general executive control processes are thought to be involved in language control: *goal maintenance*, *interference control* - including *conflict monitoring* and *interference suppression* -, *salient cue detection*, *selective response inhibition*, *task disengagement*, *task engagement* and *opportunistic planning.* According to the *Adaptive Control Hypothesis* (Green & Abutalebi, 2013), bilingual language use and the specific involved control processes adapt interdependently, that means according to the dominant interactional context and to other cognitive and linguistic factors, such as for example the age of second language acquisition or the L2 proficiency. However, as mentioned above, it remains controversial which control processes could benefit from bilingualism, and which linguistic or non-linguistic factors in bilingualism may cause a bilingual advantage, given the multi-factorial nature of bilingualism itself (Luk & Bialystok, 2013). Behavioral, neurophysiological and neuroimaging data corroborate the hypothesis that domain-general executive control is involved in bilingual language processing. At the behavioral level, in linguistic and non-linguistic tasks involving cognitive control in order to resolve conflicts, better performance has been generally observed in bilinguals compared to monolinguals. However, it is to be noted that some studies did not report such a bilingual advantage (for reviews, see e.g. Bialystok, Craik, & Luk, 2012; Costa, Hernández, Costa-Faidella, & Sebastián-Gallés, 2009; Diamond, 2010; Hilchey & Klein, 2011; Kroll & Bialystok, 2013; Tao, Marzecová, Taft, Asanowicz, & Wodniecka, 2011). During the past 20 years, significant progress concerning the study of the relation between bilingualism and executive control processes in language processing has been made due to the use of electroencephalography (EEG) which allows us to record (among others) event-related brain potentials which are time-locked to external events and therefore enable to follow millisecond by millisecond the time course of processes and sub-processes (including control processes) involved in language processing. Moreover, the use of functional magnetic resonance imaging (fMRI), known for its high spatial resolution, has provided important progress at the level of the exact cortical and subcortical localization of these cognitive processes. Several studies have shown that even if bilingualism does not necessarily lead to a behavioral bilingual advantage in executive functions, regular multiple language use leads to changes in neural processing of executive control, for instance in conflict monitoring (Kousaie & Phillips, 2012b), inhibition (Sullivan, Janus, Moreno, Astheimer, & Bialystok, 2014) or cognitive flexibility (Kuipers & Thierry, 2013). Neuroimaging data have provided empirical evidence that neuronal conflict processing is more efficient in bilinguals compared to monolinguals (Abutalebi et al., 2012). Critically, several studies revealed that the neural network involved in bilingual language control (Abutalebi, Della Rosa, et al., 2013; Buchweitz & Prat, 2013; de Bruin, Roelofs, Dijkstra, & FitzPatrick, 2014; Green & Abutalebi, 2013; Kroll & Bialystok, 2013; Luk, Green, Abutalebi, & Grady, 2012) largely overlaps with the neural network involved in domain-general cognitive control (MacDonald, Cohen, Stenger, & Carter, 2000; Shenhav, Botvinick, & Cohen, 2013; van Veen & Carter, 2006). Concerning the neuronal language control network, the following areas are involved: the anterior cingulate cortex (ACC) and the pre-supplementary motor area (pre-SMA) in conflict monitoring, the left prefrontal cortex (PFC) and the inferior frontal cortex (IFC) in the control of interference, parietal cortical areas in the maintenance of task representations, the caudate nucleus in switching between languages, and connections between basal ganglia structures and the cerebellum (Abutalebi & Green, 2007; Luk et al., 2012). The overlap between the language control and the domain-general control networks may explain the observation of a bilingual advantage for controlling information even in non-linguistic tasks such as the Simon or Eriksen flanker tasks (Bialystok et al., 2012; Kroll & Bialystok, 2013). However, some studies have also shown evidence in favor of a partially qualitative difference between domain-general control and control over bilingual language use (Calabria, Hernández, Branzi, & Costa, 2012; Magezi, Khateb, Mouthon, Spierer, & Annoni, 2012; Weissberger, Gollan, Bondi, Clark, & Wierenga, 2015). Moreover, certain cognitive and linguistic factors of bilingualism have a strong influence on control demands in bilingualism and as a consequence account for neuroplastic changes in the neural bases of executive control. Amongst the most influential factors are cited the age of acquisition of the L2, the L2 proficiency, immersion experience and the interactional context. Concerning the age of acquisition of the L2, it has been shown that simultaneous bilinguals benefit from a better control than successive bilinguals, especially in conflict monitoring, but the data are more mitigated for inhibitory processes. The L2 proficiency is thought to be the most influential linguistic factor, with a higher proficiency in general being associated with better control capacities. In contrast, to date it is not clear which control processes benefit most from an increase in L2 proficiency, i.e. conflict monitoring, inhibition or cognitive flexibility. Moreover, immersion experience and intense classroom learning are often found to be associated with structural changes in the neurocognitive language and control networks, indicating specific control demands in immersion. Finally, also the interactional context, and the frequency and pattern of language switching or language separation, have been associated with different control demands. This short overview shows that the influence of the linguistic and environmental background plays an important role for the control demands in language use. The present doctoral thesis studied the influence of different parameters in the language biography, e.g. language proficiency, immersion experience in an L2 environment or the frequency of language use, on control processes. In order to study the impact of bilingualism on conflict monitoring and interference suppression in a task involving a linguistic component, a behavioral study using a Stroop task (Study 1; Heidlmayr, Moutier, Hemforth, Courtin, Tanzmeister, & Isel, 2014) and a neurophysiological (EEG) study using a combined Stroop - negative priming task (Study 2; Heidlmayr, Hemforth, Moutier, & Isel, 2015) were carried out. In Study 1, our hypothesis was that the frequency of use of a second language (L2) in the daily life of successive bilingual individuals impacts the efficiency of their inhibitory control mechanism. Thirty-three highly proficient successive French–German bilinguals, living either in a French or in a German linguistic environment, performed a Stroop task on both French and German words. The Stroop task is assumed to tap processes of interference control - including conflict monitoring and interference suppression. Indeed, this task consists in naming the color ink of written words; conflict is operationalized by using in some trials color words that do not fit the ink color in which they are written (for example, **RED**). Moreover, 31 French monolingual individuals constituting a control group were also tested with French words. Study 1 revealed a behavioral response time advantage of bilingualism on interference control, and importantly showed that this advantage was reinforced by the frequency of use of an additional third language and modulated by the duration of immersion in an L2 environment. Study 2 aimed to disentangle the neurodynamics of three executive control processes, namely conflict monitoring, interference control (i.e., interference suppression and conflict resolution) and overcoming of inhibition using a combined Stroop - negative priming paradigm while event-related brain potentials were recorded online in 22 highly proficient but non-balanced successive French–German bilingual adults and 22 monolingual adults (control group). While the Stroop task is thought to enable to study interference control, negative priming is assumed to tap processes of overcoming of inhibition. Indeed, as in the Stroop trials, the negative priming task consists in naming the color ink of items among which some color words do not fit their ink color (incongruent trials). However, in negative priming there is an additional level of complexity: in the incongruent trials the participants not only have to ignore the orthographic information, which is in conflict with the information from the ink color which participants have to respond to but they also have to overcome the inhibition of the color name which constituted the orthographic information that has been inhibited at the previous trials (e.g. **RED**$^{\textit{n-1 trial}}$ – **GREEN**$^{\textit{negative priming trial}}$). In this study, a reduction of the effect on neurophysiological markers of inhibition has been observed for bilinguals compared to monolinguals, but only for interference suppression, i.e. in the Stroop task, the data revealed that the ERP effects were reduced in the N4 and the sustained fronto-central negative-going potential time windows in bilinguals in comparison to monolinguals. Surprisingly, no differences were observed between bilinguals and monolinguals in the negative priming condition – yet considered to be the most complex condition in terms of control – probably due to a ceiling effect in the bilingual group. Moreover, we found that the neurophysiological advantage in interference suppression was reinforced by the frequency of use of the second language. The analysis of the neurodynamics of the underlying neuronal generators showed a crucial role of the anterior cingulate cortex (ACC) in earlier time windows and the prefrontal cortex (PFC) slightly later in the realization of the combined Stroop – negative priming task, and this implication of neuronal sources was more pronounced in bilinguals compared to monolinguals. Taken together, we proposed that the electroencephalographical data of Study 2 lend support to a cascading neurophysiological model of executive control processes, in which ACC and PFC may play a determining role in managing cognitive conflict situations, but at different moments. Finally, Study 3, under the hypothesis that some control processes involved in bilingualism are domain-general control processes, aimed at examining whether bilinguals benefit from their enhanced abilities to control language interferences for controlling inappropriate information in a non-linguistic task, namely an oculomotor one. Thus, the impact of bilingualism on motor control was examined in a neurophysiological (EEG) study using an antisaccade task (Study 3; Heidlmayr, Doré-

Mazars, Aparicio, & Isel, submitted). The antisaccade task consists in inhibiting an eye movement that is automatically generated when a visual target appears in the peripheral visual field of an individual and in voluntarily changing the motor program of the eye movement to re-orientate the eye toward the opposite location of the visual target. Critically, in the present experiment we performed the measures of the ERP markers of control at three phases of the movement: the ‘preparation’ (cue-locked), ‘implementation’ (target-locked) and ‘execution’ (saccade-locked) phases and we observed how the ERP markers in each of these phases of processing vary in bilinguals in comparison with monolinguals. In Study 3, we administrated to 19 highly proficient late French-German bilingual participants and to a control group of 20 French monolingual participants an antisaccade task. Our main hypothesis was that an advantage in the antisaccade task should be observed in bilinguals if some properties of the control processes are shared between linguistic and motor domains. ERP data revealed clear differences between bilinguals and monolinguals. In bilinguals, an increased N2 effect size was observed, thought to reflect better efficiency to monitor conflict. Moreover, a bilingual advantage was found on effect sizes on markers reflecting inhibitory control (response inhibition), i.e. cue-locked positivity, the target-locked P3 and the saccade-locked presaccadic positivity (PSP), and this inhibitory advantage was reinforced by the L2 proficiency and the immersion experience. Furthermore, effective connectivity analyses on the source level, i.e. the analysis of how the activity in one brain region influences the activity in another brain region, indicated that bilinguals rely more strongly on ACC-driven control, whereas monolinguals on PFC-driven control. Taken together, our combined ERP and effective connectivity findings in Study 3 may reflect a dynamic interplay between strengthened conflict monitoring, associated with subsequently more efficient inhibition in bilinguals. This observation indicates that conflict processing in a non-linguistic task is more efficient in bilinguals. In conclusion, the main findings collected in the present doctoral thesis can be summarized as follows (1) A behavioral and neurophysiological evidence of enhanced conflict monitoring and inhibition in bilingualism, (2) A more efficient dynamic interplay between anterior cingulate cortex and the prefrontal cortex in executive control in bilingualism, and (3) A modulatory impact of the individual language background on executive control efficiency. The present findings lend support to psycholinguistic theories postulating that domain-general executive control processes whose characteristics are probably shared between different cognitive and motor domains are involved in the control of languages in bilingualism. Moreover, the activation and interplay of the neuronal generators suggest that the experience in handling more than one language leads to more efficient neuronal processing of conflict monitoring and inhibitory control, amongst others in the ACC and the PFC, and also leads to a more efficient interaction between these regions. This research contributes to our understanding of neuroplastic changes during sustained multiple language use and of the neuroplastic adaptations underlying strengthened domain-general executive control. The sustained possibility of suffering interferences between languages is inherent to the bilingual experience and appears to lead to a *reinforcement* of conflict monitoring and inhibitory control in order to meet communicatory requirements in both languages. To reduce cross-language interferences, a reinforcement of conflict monitoring and inhibitory control probably takes place, which allows the bilingual individual to adapt to the communicative constraints imposed by each of the languages in a bilingual linguistic context. The investigation of the neurodynamics underlying linguistic and non-linguistic control in bilinguals and monolinguals has revealed that certain control processes involved in language control could also be involved in the processing of conflict in non-linguistic domains, such as oculomotricity. Future neuroimaging and neurophysiological research should aim at clarifying the influence of the control capacity in different situations of linguistic conflict. Moreover, the systematic investigation of the interactional context of languages and the frequency and pattern of language use and language switching will allow for a better understanding of the fine adjustment of the control system as a function of the specific linguistic and environmental constraints. Finally, the study of individual differences including longitudinal approaches may provide precious information and should be privileged in the future.

RESUME EN FRANÇAIS

En psycholinguistique, il a été montré que chez un individu bilingue, la co-activation permanente, mais à des niveaux différents, de ses différentes langues ainsi que le besoin d'adaptation à l'environnement linguistique conduit à un renforcement des mécanismes du contrôle cognitif, ce dans le but de répondre de manière efficace aux contraintes communicatives dans chacune des langues. L'objectif de la présente thèse de doctorat était d'examiner la relation entre le bilinguisme et le contrôle exécutif général. À ce jour, la nature de l'implication du contrôle général dans l'utilisation de plusieurs langues reste controversée. L'objectif principal consistait à contribuer à la compréhension de la dynamique cognitive et neuronale de l'implication du contrôle exécutif général dans le traitement du langage bilingue. Des recherches ont montré que le traitement d'une langue seconde (L2) implique les mêmes aires cérébrales que celles de la première langue (L1), et ceci indépendamment de l'âge d'acquisition de la L2 (Abutalebi, 2008). Cependant, l'acquisition et l'utilisation d'une L2, en plus de la mise en jeu comme dans la L1 de régions corticales connues pour sous-tendre les fonctions langagières, implique la participation de régions du cerveau connues pour être le siège du contrôle cognitif. La mise en œuvre de mécanismes de contrôle exécutif général chez les bilingues est supposée refléter la nécessité de contrôler les interférences que la langue dominante, hautement automatisée, peut exercer sur une langue moins automatisée, en général la L2 (Abutalebi, 2008). Bien que l'implication des fonctions exécutives dans le traitement du langage bilingue ait été abondamment explorée, dans des études comportementales et d'imagerie cérébrale, beaucoup de questions restent à élucider notamment concernant la nature exacte des processus de contrôle impliqués. Différents modèles neurocognitifs du traitement du langage ont discuté l'implication des processus de contrôle exécutif général dans le traitement du langage, e.g. Fedorenko and Thompson-Schill (2014), ou encore le modèle *Memory Unification Control* (MUC) proposé par Hagoort (2005, 2014). Selon Hagoort, l'aire de Broca (cortex frontal inférieur, BA 44 et 45) n'est pas nécessairement une région spécifique au processus langagiers mais elle remplirait la fonction d'unification (*binding*) langagière grâce à des connexions avec les aires spécifiques du langage. De plus, dans le modèle MUC proposé par Hagoort, les processus de contrôle seraient pris en charge par le cortex préfrontal (*PFC*) ainsi que par le cortex cingulaire antérieur (*Anterior Cingulate Cortex ou ACC*), entre autres (Hagoort, 2005, 2014). De façon similaire, Fedorenko et Thompson-Schill (2014) considèrent que le traitement du langage implique des processus de contrôle exécutif général, dont les bases neurales incluent des régions préfrontales, frontales inférieures et pariétales. En outre, au-delà du contrôle également nécessaire lors de l'utilisation de la langue maternelle, les individus qui ont appris une ou plusieurs langues étrangères ont des besoins de contrôle spécifiques et en général accrus (Blumenfeld & Marian, 2013). Comme évoqué, il est aujourd'hui largement admis par la communauté scientifique des psycholinguistes que chez les individus bilingues, les deux langues sont activées même si le contexte ne requiert l'utilisation que de l'une d'entre elles (accès non-sélectif aux langues ; Brysbaert, 2003 ; Dijkstra, 2005 ; Hoshino & Thierry, 2011 ; Van Heuven et al., 1998). Par conséquent, des processus de contrôle sont nécessaires afin de réduire les interférences entre les langues (Blumenfeld & Marian, 2013 ; Costa, Albareda, et al., 2008 ; Runnqvist et al., 2012), et d'adapter l'utilisation des langues à chaque contexte langagier ainsi qu'environnemental (Green & Abutalebi, 2013). Parmi les modèles les plus pertinents sur le contrôle des langues chez le bilingue, certains font l'hypothèse d'un accès non-sélectif aux langues, on peut citer : l'hypothèse du contrôle adaptatif (*Adaptive Control Hypothesis*) par Green et Abutalebi (2013) et le modèle du contrôle inhibiteur (*Inhibitory Control* ; IC ; Green, 1998) ; le modèle d'activation interactive bilingue (*Bilingual Interactive Activation+* ; BIA+) par Dijkstra et van Heuven (2002 ; Van Heuven et al., 1998) ; le modèle d'accès au lexique proposé par Costa, Miozzo et Caramazza (1999) / Costa (2005) ; et enfin le modèle du rôle du contrôle exécutif dans le bilinguisme par Stocco, Yamasaki, Natalenko, et Prat (2014). Le modèle du contrôle inhibiteur (*Inhibitory Control* ; IC ; Green, 1998) postule que le contrôle du traitement du langage chez le bilingue implique différents niveaux de contrôle, i.e. un processus de contrôle ascendant de bas-en-haut (bottom-up ; exogène) et un processus de contrôle descendant (top-down ; endogène). Dans le modèle IC, le langage est considéré comme une forme d'action communicative, dans laquelle les schémas de tâches linguistiques et non-linguistiques (des dispositifs ou réseaux mentaux dédiés à des tâches différentes) jouent un rôle central. Ces schémas de tâche sont activés pour exécuter des tâches linguistiques (par exemple la production d'un mot) ainsi que non-linguistiques et le contrôle exécutif général exerce un contrôle descendant (top-down) sur l'activation des schémas de tâches en compétition selon le contexte linguistique. Chez les individus monolingues, les schémas de tâche existent mais chez les individus bilingues ils servent additionnellement à sélectionner la langue cible et à inhiber toute langue non-cible dans un certain contexte communicatif. La sélection ou l'inhibition d'une langue fonctionne à l'aide de marqueurs de langue (*language tags*). La plus récente version de l'hypothèse du contrôle adaptatif (*Adaptive Control Hypothesis*) formulée par Green et Abutalebi (2013) postule que des processus de contrôle exécutif généraux à plusieurs domaines sont impliqués dans le contrôle des langues. Compte tenu que la co-activation des langues ainsi que différentes façons de les utiliser caractérisent le bilinguisme, les individus bilingues solliciteraient plus régulièrement leurs processus de contrôle que ne le feraient des individus n'utilisant que rarement voire jamais une langue seconde (« monolingues »). Par conséquent une meilleure efficacité de ces processus de contrôle devrait être attendue chez les individus bilingues. Selon le contexte interactionnel – qui est défini par la fréquence et le pattern de changements entre les langues ou les patterns d'indépendance des langues – parmi les processus de contrôle exécutif généraux à plusieurs domaines sont supposés être impliqués dans le contrôle des langues : maintien d'un but (*goal maintenance*), contrôle des interférences (*interference control*) – incluant la gestion de conflits (*conflict monitoring*) et la suppression d'interférences (*interference suppression*) -, détection d'indices saillants (*salient cue detection*), inhibition sélective d'une réponse (*selective response inhibition*), désengagement d'une tâche (*task disengagement*), engagement dans une tâche (*task engagement*) et le planning opportuniste (*opportunistic planning*). Selon l'hypothèse du contrôle adaptatif (*Adaptive Control Hypothesis* ; Green & Abutalebi, 2013), l'utilisation des langues chez le bilingue et les processus de contrôle impliqués s'adaptent de façon interdépendante, c'est-à-dire selon le contexte interactionnel dominant et selon d'autres facteurs cognitifs et linguistiques tels que par exemple l'âge d'acquisition de la L2 ou le niveau d'efficience dans celle-ci. Pourtant, la question des processus de contrôle renforcés dans le bilinguisme ou encore celle des facteurs linguistiques et non-linguistiques du bilinguisme qui produiraient un avantage du bilinguisme tout en tenant compte de la nature multi-factorielle du bilinguisme restent à l'heure actuelle en débat (Luk & Bialystok, 2013). Des données comportementales, neurophysiologiques ainsi que de neuro-imagerie corroborent l'hypothèse de l'implication du contrôle exécutif général dans le traitement du langage bilingue. Au niveau comportemental, dans des tâches linguistiques ainsi que non-linguistiques nécessitant un contrôle cognitif afin de résoudre des conflits, de meilleures performances ont été trouvées chez les bilingues que chez les monolingues. Toutefois, il est important de noter que d'autres études, en moins grand nombre certes, n'ont pas trouvé d'avantage du bilinguisme lors de la réalisation de tâches expérimentales impliquant un conflit (pour des revues, voir e.g. Bialystok, Craik, & Luk, 2012 ; Costa, Hernández, Costa-Faidella, & Sebastián-Gallés, 2009 ; Diamond, 2010 ; Hilchey & Klein, 2011 ; Kroll & Bialystok, 2013 ; Tao, Marzecová, Taft, Asanowicz, & Wodniecka, 2011). Des avancées significatives concernant la neurodynamique des processus de contrôle cognitif chez des individus utilisant plus ou moins régulièrement une seconde langue ont été réalisées au cours des vingt dernières années, notamment grâce à l'utilisation des techniques : (1) neurophysiologiques d'électroencéphalographie (EEG) et de magnétoencéphalographie (MEG), connues pour leur haute résolution temporelle (de l'ordre de la milliseconde) et (2) d'imagerie cérébrale telle que l'imagerie par résonance magnétique fonctionnelle (IRMf) présentant une haute résolution spatiale (de l'ordre du millimètre). Les observations dans différentes études suggèrent qu'en dépit d'une absence d'avantage du bilinguisme mesurable au niveau comportemental, l'utilisation soutenue de plusieurs langues peut conduire à des changements de réponse neuronale du contrôle exécutif, notamment en ce qui concerne la gestion de conflits (Kousaie & Phillips, 2012b), l'inhibition (Sullivan et al., 2014) ou la flexibilité cognitive (Kuipers & Thierry, 2013). Des données de neuro-imagerie ont apporté la preuve empirique que le traitement neuronal de conflits est plus efficace chez les bilingues que chez les monolingues (Abutalebi et al., 2012). En outre, maintes observations soulignent qu'il y a un large recouvrement des aires corticales du contrôle des langues (Abutalebi, Della Rosa, et al., 2013 ; Kroll & Bialystok, 2013 ; Luk et al., 2012) avec les aires sous-tendant les processus de contrôle exécutif concernant plusieurs domaines (MacDonald et al., 2000 ; Shenhav et al., 2013 ; van Veen & Carter, 2006). Toutefois, notons, que certaines données en neuro-imagerie suggèrent une séparation partielle de ces deux réseaux de contrôle (Calabria et al., 2012 ; Magezi et al., 2012 ; Weissberger et al., 2015). Les régions cérébrales suivantes font partie du réseau de contrôle des langues : le cortex cingulaire antérieur (*ACC*) et l'aire motrice pré-supplémentaire (*pre-SMA*) dans la gestion de conflits ; le cortex préfrontal (*PFC*) et le cortex frontal inférieur (*IFC*) dans le contrôle des interférences ; des régions dans le cortex pariétal dans le maintien des représentations de la tâche ; en outre, le noyau caudé, lors du changement des langues ; certaines connections entre les ganglions de la base et le cervelet.

En outre, dans le bilinguisme certains facteurs cognitifs et linguistiques influencent les processus de contrôle des langues et par conséquent les changements neuroplastiques dans les bases neurales du contrôle exécutif. Parmi ces facteurs les plus influents, on compte l'âge d'acquisition de la L2, le niveau d'efficience dans celle-ci, l'expérience d'immersion et le contexte interactionnel lié à la fréquence et au pattern de changements de langues. Concernant l'âge d'acquisition de la L2, des recherches ont mis en évidence que des bilingues simultanés bénéficient d'un meilleur contrôle que les bilingues successifs, notamment au niveau de la gestion de conflits. En revanche, concernant les processus inhibiteurs, les données sont moins convergentes. Une bonne efficience dans la L2 apparaît comme le facteur linguistique le plus influent. En revanche, on ne sait pas encore quels processus de contrôle bénéficient le plus d'une amélioration de l'efficience dans la L2, i.e. la gestion de conflits, l'inhibition ou la flexibilité cognitive. En outre, les phases d'apprentissage intenses dans le cadre de cours mais surtout l’expérience d’immersion sont accompagnées par des changements structurels dans les réseaux neuronaux langagiers et de contrôle, ce qui semble indiquer le besoin de contrôle spécifique pendant l’immersion. Ce bref aperçu montre que l’influence de l’arrière-plan langagier et environnemental individuel joue un rôle déterminant sur l’exigence de contrôle lors de l’utilisation des langues.

La présente thèse de doctorat a étudié l’influence de différents paramètres de la biographie linguistique, tels que le niveau d’efficience, l’expérience d'immersion dans un environnement L2 ou la fréquence d’utilisation des langues sur différents processus de contrôle. Afin d’explorer l’impact du bilinguisme sur le traitement de conflits dans une tâche impliquant une composante linguistique, une étude comportementale utilisant une tâche de Stroop (Etude 1 ; Heidlmayr, Moutier, Hemforth, Courtin, Tanzmeister, & Isel, 2014) et une étude neurophysiologique (EEG) utilisant une tâche combinée de Stroop et d’amorçage négatif (Etude 2 ; Heidlmayr, Hemforth, Moutier, & Isel, 2015) ont été conduites.

Dans l’étude 1, nous avons émis l’hypothèse que la fréquence d’utilisation d’une langue seconde dans la vie quotidienne des bilingues tardifs peut influencer l’efficacité de leur mécanisme de contrôle inhibiteur. Trente-trois bilingues tardifs français-allemand ayant un haut niveau d’efficience dans leur L2 et vivant dans un environnement linguistique, soit français soit allemand, ont effectué une tâche de Stroop avec des mots français et allemands. De plus, 31 monolingues français constituant un groupe contrôle ont effectué la même tâche en français uniquement. L’étude 1 a révélé un avantage du bilinguisme sur le contrôle inhibiteur, qui est renforcé par la fréquence d’utilisation d’une troisième langue mais également modulé par la durée d’immersion dans un environnement L2. La neurodynamique des processus de contrôle dans le traitement des conflits linguistiques a été examinée dans l'étude 2. Cette étude s’intéresse à l’impact du bilinguisme sur l’activité neuronale dans différents processus de contrôle exécutif généraux à plusieurs domaines, notamment la gestion de conflits, la mise en place du contrôle, c'est-à-dire la suppression d'interférences et la résolution de conflits, ainsi que la levée de l'inhibition. Un enregistrement des potentiels évoqués a été réalisé alors que 22 bilingues tardifs français-allemand avec un haut niveau d'efficience dans leur L2 ainsi que 22 monolingues français effectuaient une tâche combinée de Stroop et d'amorçage négatif. Pour la tâche de Stroop, les données ont montré une réduction de l'effet neurophysiologique N4, supposé refléter le processus de suppression d'interférences, chez les bilingues par rapport aux monolingues ; de plus, une réduction d'un effet tardif, c'est-à-dire une négativité tardive dans la durée (*late sustained negative-going potential*), a également été observée chez les bilingues. Cet avantage du bilinguisme au plan neurophysiologique est renforcé par la fréquence d'utilisation de la deuxième langue. L'analyse des générateurs neuronaux sous-jacents aux effets mesurés sur le scalp a montré le rôle prépondérant du cortex cingulaire antérieur pour les effets précoces (N2 et N4) et du cortex préfrontal à une étape ultérieure (N4 et la négativité tardive) dans la réalisation de la tâche de Stroop et d'amorçage négatif. L'implication de ces deux générateurs neuronaux est plus prononcée chez les bilingues. Prises dans leur ensemble, les données de la deuxième étude corroborent un modèle neurophysiologique postulant la mise en œuvre en cascade de processus de contrôle exécutif probablement pris en charge (en partie) par le cortex cingulaire antérieur et le cortex préfrontal. Enfin, l'étude 3 visait à montrer que les processus de contrôle impliqués dans le bilinguisme sont généraux, partagés entre les domaines cognitifs linguistique et non-linguistiques, notamment oculomoteur. Ainsi, l'impact du bilinguisme sur le contrôle oculomoteur a été évalué au niveau neurophysiologique (EEG) lors de la réalisation d'une tâche antisaccades (Etude 3 ; Heidlmayr, Doré-Mazars, Aparicio, & Isel, submitted). Dans cette troisième étude, 19 bilingues tardifs français-allemand avec un haut niveau d'efficience dans leur L2 et un groupe contrôle constitué de 20 participants monolingues français ont effectué une tâche antisaccades, i.e. une tâche oculomotrice spécifique, impliquant un contrôle du mouvement des yeux. Dans cette tâche, une saccade automatique vers une cible visuelle présentée sur l'écran d'un ordinateur devait être supprimée pendant qu'un mouvement oculaire volontaire dans la direction opposée devait être effectué. L’hypothèse principale est qu’un avantage du bilinguisme devrait exister dans cette tâche, si certaines composantes des processus de contrôle sont partagées entre les domaines linguistique et oculomoteur. Les potentiels évoqués ont montré des différences claires entre les bilingues et les monolingues. Chez les bilingues, un effet N2 plus important que chez les monolingues a été mis en évidence, ce qui peut refléter une meilleure performance de gestion de conflits. En outre, l’étude a mis en évidence un avantage du bilinguisme pour les marqueurs neurophysiologiques de l’inhibition (inhibition d’une réponse ; positivité liée à la présentation de l’indice, P3 liée à la présentation de la cible et la positivité pré-saccadique), et cet avantage inhibiteur se trouve renforcé par l’efficience dans la L2 et par l’expérience d’immersion. De plus, les analyses de la connectivité effective, c’est-à-dire l’influence de l’activité dans une région neuronale sur l’activité d’une autre région ont révélé le rôle primordial du cortex cingulaire antérieur chez les bilingues, alors que chez les monolingues c’est le cortex préfrontal qui semblerait être plus impliqué. Combinées entre elles, les données en potentiels évoqués ainsi que celles de la connectivité effective suggèrent une interaction dynamique entre la gestion de conflits plus performante suivie par des processus d’inhibition plus efficaces chez les bilingues. Cette observation indique que le traitement de conflits dans une tâche non-linguistique est plus efficace chez les bilingues.

Pour conclure, les principaux résultats de la présente thèse de doctorat peuvent être résumés comme suit : (1) Mise en évidence aux plans comportemental et neurophysiologique d’une efficacité plus grande des processus de gestion de conflits et d’inhibition chez les bilingues ; (2) Interaction entre le cortex cingulaire antérieur et le cortex préfrontal dans le contrôle cognitif plus importante chez les bilingues, et (3) Impact modulateur de l’arrière-plan linguistique des participants sur l’efficacité du contrôle. Ces données corroborent les modèles psycholinguistiques de traitement du langage bilingue postulant que des processus de contrôle exécutif général sont impliqués dans le contrôle des langues en situation de bilinguisme. De plus, la dynamique d’activation des générateurs neuronaux suggère que l'expérience de la gestion de plusieurs langues rend plus efficace non seulement le traitement neuronal de la gestion de conflits et du contrôle inhibiteur, entre autres dans le cortex cingulaire antérieur et dans le cortex préfrontal, mais rend aussi plus efficace l'interaction entre ces générateurs neuronaux. Ces recherches contribuent à la compréhension des changements neuroplastiques lors de l'utilisation soutenue de plusieurs langues et révèlent les adaptations sous-tendant le renforcement du contrôle exécutif général. Le risque permanent qu'une langue, en particulier si elle est faiblement automatisée, subisse des interférences à différents niveaux grammaticaux venant d'une autre langue est inhérent à l'expérience bilingue. Afin de limiter un tel risque, un renforcement de la gestion de conflits et du contrôle inhibiteur est mis en place, dans le but de répondre aux exigences communicatives imposées par chacune des langues, dans un contexte linguistique bilingue. Des recherches futures devront clarifier l'influence de la capacité de contrôle dans différentes situations de conflit linguistique. Par ailleurs, l'étude systématique du rôle du contexte d'interaction ainsi que de la fréquence et du pattern de changements entre les langues permettra de mieux comprendre l'ajustement très fin du système de contrôle. Enfin, il serait opportun d'analyser dans nos travaux les différences individuelles. Par ailleurs, une approche longitudinale dans l'analyse de ces différences permettrait l'accès à de nouvelles informations et cette méthode devrait être privilégiée dans le futur.

PART 1: INTRODUCTION AND LITERATURE REVIEW

1. CONTROL PROCESSES IN MULTIPLE LANGUAGE USE

1.1. DEFINING BILINGUALISM

Worldwide, the linguistic diversity is large with approximately 4500 to 6000 languages (Hagège, 2009, p. 170). Moreover, amongst the speakers of these languages, individuals using more than one language largely outnumber individuals who use only a single language for any given communicative interaction in their life (UNESCO, 2003). Monolingualism has for a long time been considered as the norm for language use, but the past 20 years of research in linguistics have brought about a new insight and to a certain degree a rectification of this view of bilingualism, in that multiple language use is the prevalent case of language use worldwide and monolingualism rather the exception (Kroll, Bobb, & Hoshino, 2014). The vast majority of bilinguals are so-called *unbalanced* bilinguals for whom one language is more dominant than the other, and a far smaller proportion are considered as *balanced* bilinguals with comparable language dominance (De Groot & Kroll, 1997, p. 1). If bilingualism is defined as the knowledge of two distinct languages within a single individual, then every individual who produces fluent utterances in two languages, but also every individual who is in the process of acquiring/learning a second language (L2) shall be considered as bilingual. Consequently, bilingualism does not need to be the end point of second language learning but can be regarded as a continuum with respect to the degree of second language knowledge (Dufour, 1997, p. 304).

In a review on the definition of bilingualism, Baetens Beardsmore (1986, p. 1) notes that despite a common understanding of the terms *bilingual* and *bilingualism* amongst researchers as well as laymen, specialists differ in their specific definitions and/or remain very general. This may partially be due to the manifold appearances of multiple language use. One of the earliest linguistic definitions has been given by Weinreich (1953, p. 5), who claims that “the practice of alternatively using two languages will be called here *bilingualism*, and the persons involved *bilingual*” (Weinreich, 1953, p. 5). Similarly, also a more recent definition states that “a bilingual individual is someone who controls two or more languages” (Hakuta, 2003). An accepted definition considers *bilingualism* – on the level of an individual or a community - as the fluent usage of two languages, as well as the state or situation that results from it (CNRTL, 2015a). However, since the very beginning of bilingualism research there is an awareness of the gradation of bilingual language proficiency: Bloomfield (1935), characterizes bilingualism as the “native-like control of two languages” (Bloomfield, 1935, pp. 55–56), but, in contrast, later also claims that “one cannot define a degree of perfection at which a good foreign speaker becomes a bilingual: the distinction is relative” (Bloomfield, 1935, pp. 55–56). The focus on the gradual and multifaceted nature of bilingualism is strengthened in more recent definitions. Grosjean (1996, p. 1) defines as bilinguals “those people who use two (or more) languages (or dialects) in their everyday lives”. This definition includes a huge diversity of individuals who share at least the feature that they lead their lives with at least two languages (Grosjean, 1996). Grosjean (1998) gives an overview of the differences that exist between bilingual individuals and the problems that can occur when cross-study comparisons and generalizations are drawn. The multiplicity of parameters involves factors deriving from the bilingual language history and the language relationship (i.e. time and manner of respective language acquisition, the cultural context and pattern of language use), from language stability (i.e. a language still being acquired or being restructured due to a change of the linguistic environment), language proficiency, language modes (i.e. monolingual, bilingual – with varying patterns of code-switching or -mixing or borrowings) or biographical variables (i.e. age, sex, socioeconomic and educational status; Grosjean, 1998). A major problem in most of the psycholinguistic studies on bilingualism is that many of these variables are not being assessed which consequently leads to limitations in the meaningfulness of comparison between studies.

The age of acquisition (AoA) of a second language (L2) is an important feature used to characterize different types of bilingualism, and allows for distinguishing between *simultaneous* and *sequential* bilingualism, i.e. differentiating if the two languages were acquired from the same age – earliest childhood - on or if the second language (L2) was acquired after the first language (L1; Hakuta, 2003). A similar distinction is the one between *early* vs. *late* bilingualism, but this distinction additionally enables to distinguish between different AoA of L2 in sequential bilingualism. *Late*, *sequential* or also *successive* (Meisel, 2007) bilingualism indicates that the L2 has been acquired after the L1, while the exact age of acquisition separating *early* from *late (sequential, successive)* bilingualism varies in the literature from a rather early AoA, i.e. the age of 3 on (Hakuta, 2003), to later AoA, i.e. the age of 7 years on (Meisel, 2007). Finally, bilingualism is not an isolated cognitive and social phenomenon, but is in a complex way interdetermined with biculturalism (Grosjean, 1996), cognitive as well as social factors. As for the cognitive factors, multiple cognitive domains relate to bilingual language processing, such as emotion or executive control. For instance, emotional information is processed in different ways in the first and second languages (Conrad, Recio, & Jacobs, 2011; Grosjean, 2010; Marian & Kaushanskaya, 2008; Pavlenko, 2008, 2012; Sheikh & Titone, 2015) and executive control processes are required to adapt to different linguistic environments, speakers and accents (Baum & Titone, 2014; Green & Abutalebi, 2013; P. Li, Legault, & Litcofsky, 2014). The relation between executive control and bilingual language processing will be further elaborated in this doctoral thesis. Concerning the social factors, it has been suggested to distinguish the case when second language acquisition is a constraint, i.e. *circumstantial bilingualism* which frequently occurs with migration, from the case when it is a choice, i.e. *elective bilingualism* where mastery of the second language is intended to improve the individual's value in society (Valdes & Figueroa, 1994); another distinction has been made between *subtractive bilingualism* where bilinguals acquire or learn an L2 competence at the expense of their L1 and *additive bilingualism* where bilinguals improve their L2 competence without losing the L1 (Lambert, 1974; for a review, see Butler & Hakuta, 2004).[1]

Language contact is the human situation in which an individual or a group is required to use two or more languages, and therefore constitutes the concrete event that causes bilingualism, including the cross-language interferences that can arise (Perret, 1999). Thus, when two idioms, i.e. the languages of a community (in general a nation or a people), or - from a linguistic perspective - the ensemble of the means of expression of a community considered in its specificity (CNRTL, 2015a, 2015c) are in contact, the issue of grammatical transfer (among them, interferences) between these idioms is raised. Grammatical transfer can be positive or negative and can occur at different linguistic levels, i.e. phonetic, phonological, morphosyntactic, syntactic or lexical levels. Interference between languages is a crucial feature of bilingualism, and consequently the question arises of how languages are controlled in order to reduce these cross-language interferences. The co-activation of different sources of linguistic information in different languages can generate competitions between this information. Some partially interference-related disadvantages observed in proficient bilingualism are, e.g., slower lexical access, more frequent tip-of-the-tongue states and unintentional cross-language intrusions (Ivanova & Costa, 2008; Runnqvist & Costa, 2011). However, these disadvantages are also partly due to the overall larger lexicon in bilinguals, when the lexical items of both languages are taken together (the individual language lexica are however probably smaller; Kroll, Dussias, Bogulski, & Kroff, 2012). Several influential psycholinguistic models of bilingual language processing postulate the involvement of domain-general executive control, in managing the use of two languages, e.g. in order to reduce the

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[1] Moreover, a rather controversial classification of bilingualism types which had strong influence for a long time is the *coordinate-compound-subordinate* distinction (for a review, see Grosjean, 1982, pp. 240–244). In *coordinate bilingualism* the words of the two languages have completely separate meanings, in *compound bilingualism* words of two languages conjure up the same reality, i.e. have the same meaning in case they are translation equivalents and in *subordinate bilingualism*, lexical processing in the weaker language is mediated via the stronger language. Moreover, it has been claimed that *coordinate bilingualism* develops through experience in contexts where the two languages are rarely interchanged while *compound* (and *subordinate*) *bilingualism* develops in fused contexts, e.g. formal language learning at school or continual switching from one language to the other. However, the definitions of these three types of bilinguals differ among authors and the existence of this distinction is disputed (Grosjean, 1982, p. 244).

cross-language interference at different linguistic levels. In psychology, *domain-general* designates a constraint or function that applies to all actions and properties of the human mind and is often opposed to the notion *domain-specific* which designates a constraint or function that applies to some but not all actions and properties of the human mind (Frensch & Buchner, 1999, p. 141). Two of these influential models are the *Inhibitory Control Model* (Green, 1998) and the *Bilingual Interactive Activation+* (BIA+) model (Dijkstra & van Heuven, 2002; Van Heuven et al., 1998; cf. section 1.3.2). Following from these models, the permanent use of domain-general executive control in multiple language use is thought to lead to a strengthening of these control processes in the long run. This idea is corroborated by findings of specific linguistic and cognitive advantages, e.g. in cognitive inhibition[2] (Ivanova & Costa, 2008; Kroll & Bialystok, 2013; Michael & Gollan, 2005; Runnqvist & Costa, 2011), or working memory[3] (Michael & Gollan, 2005). Moreover, the activation of neuronal regions involved in executive control processes, e.g. the caudate nucleus and fusiform regions, has been shown to be predictive of the success in acquiring L2 literacy skills (Tan et al., 2011). Importantly, the research on bilingualism has brought about interesting new insight into the relation between language processing, and specifically bilingual language use, and executive functions, such as inhibition, or working memory. Bilingualism may influence the capacity in these cognitive functions but bilingual language use may also be influenced by individual differences in the capacity of these cognitive functions (Michael & Gollan, 2005). The relation between bilingual language processing and executive control will be further dealt with in the subsequent sections, but first an outline of theoretical accounts and empirical observations on bilingual language learning and acquisition as well as of the mental representation of the two languages will be given.

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[2] Inhibition is one of the principal executive functions (Miyake et al., 2000), cf. section 2.

[3] *Working memory* is defined as a temporary memory that is used to plan and carry out behavior (Miller, Galanter, & Pribram, 1960). It involves both short-term storage (with separate storage of verbal-phonological and visual-spatial representations) and executive processes that manipulate stored information (Baddeley & Hitch, 1974) and its capacity strongly depends on attentional and inhibitory control capacities (Cowan, 2008; Kane, Bleckley, Conway, & Engle, 2001).

1.2. LEXICON AND GRAMMAR IN THE FIRST AND SECOND LANGUAGE

1.2.1. SECOND LANGUAGE LEARNING AND ACQUISITION

In psycholinguistics, two fundamental concepts are the *mental lexicon* of a person, i.e. the ensemble of memorized words of a language, and the *mental grammar* of a person, i.e. the set of rules that govern the form and meaning of words and sentences in a language (Miller, 1996; Nowak, 2001; Pinker, 1999; Ullman, 2001b). As for the mental lexicon, a slightly different definition is given by Paradis (2004, 2009) who makes a distinction between the *lexicon*, i.e. the set of implicit grammatical properties of items, and *vocabulary*, i.e. the ensemble of items which are form-meaning pairs that are stored in declarative memory (Paradis, 2004, 2009). Concerning the mental grammar, in first language acquisition[4] it is picked up by bottom-up rule extraction in a natural linguistic environment. However, in late second language learning, grammatical rules are in many cases first appropriated in a conscious, explicit way (explicit knowledge) and become more and more automatic with frequency of L2 use (implicit knowledge of grammatical rules; Paradis, 2009). Moreover, unlike a child learning his mother tongue, an adult, late learner of a second language, already has a well-organized linguistic system that will interfere during learning of the second language and therefore can, in some cases, slow learning. Moreover, adult second language learners need feedback, e.g. alerting or correction of errors in their second language use, for realizing grammatical features that they would otherwise not perceive (because these features and an implicit ‘feeling of correctness’ have not yet been implicitly acquired). The mastering of a given grammatical phenomenon both in production and perception in second language learners is also influenced by the fact whether this phenomenon (for example, the distinctive value of a phonetic cue such as the voiced-voiceless distinction or the short-long vowel distinction) does or does not exist in the native language of the learner. Indeed, at the phonological level for

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[4] For language appropriation processes, one usually distinguishes between *language acquisition*, i.e. a subconscious process which consists of the appropriation of implicit knowledge or implicit linguistic competence, and *language learning*, i.e. the appropriation of conscious, explicit knowledge of the second language, its rules, being aware of them and being able to talk about them (Krashen, 1982).

example, when a phonetic contrast existing in the L2 is not present in the L1, then at a certain stage of the learning process, the learner will be phonologically deaf to this phenomenon (the concept of phonological deafness proposed by Polivanov (1931) and then reconsidered by Troubetzkoy (1939) who proposed the notion of phonological filter). Flege (1995) hypothesized that phonemes of a foreign language are more difficult to learn if they are similar (but not identical) to the ones in the mother tongue: the learner does not hear the difference.

To come back to the issue of feedback information, it adds to the explicit knowledge of the L2 learners and can then be integrated in explicitly constructed utterances. Subsequently, the repeated use of this given feature in different forms of explicitly constructed utterances increases the input to the assumed implicit acquisition mechanisms and hence increases the probability that it becomes implicitly acquired through pattern extraction from the input. Stronger activation of explicit knowledge – based on declarative memory - will lead to more correct and fluent L2 output. Thus, focused L2 instruction guiding through the specific difficulties of the L2 for the learner can – even if indirectly, as previously described - facilitate and accelerate L2 grammar acquisition. To sum up, the process of L2 grammar acquisition (implicit knowledge/implicit linguistic competence) is independent from its learning (explicit knowledge), but the two are indirectly related. Adult second language learners need to explicitly learn (at least some aspects of) a language, in order to be able to use a certain number of utterances. By doing so, grammatical features and structures become repeatedly used and hence acquired. The acquisition processes itself may function in a similar way as it does in children, but probably less efficiently (Paradis, 2009, p. 106s). In the following sections, two of the most influential models of the processes taking place during second language learning and acquisition are presented, i.e. the *Revised Hierarchical Model* (RHM) by Kroll and Stewart (1994; Kroll, Van Hell, Tokowicz, & Green, 2010) describing processes at the lexical level, as well as two emergentist accounts, i.e. the *Unified Competition model* (MacWhinney, 2008, 2012) for processes on the sentence level and the

DevLex model (P. Li, Farkas, & MacWhinney, 2004; P. Li, Zhao, & MacWhinney, 2007) at the lexical level. Finally, in order to understand theories of second language learning and acquisition one further issue needs to be mentioned, namely the effect of the age of second language acquisition and the discussion of a potential *critical period* in language acquisition, which is controversial in psycholinguistics. Age of acquisition (AoA) is considered as one of the most determining factors for the ultimate proficiency attainable in a second language (L2), and the L2 AoA has been found to be negatively correlated with L2 proficiency (DeKeyser & Larson-Hall, 2005). However caution is at order before drawing firm conclusions regarding the exact role of AoA in second language learning. For example, in an fMRI study with Italian-German bilinguals who learned the second language at different ages and had different proficiency levels, Wartenburger, Heekeren, Abutalebi, Cappa, Willringer and Perani (2003) showed that the pattern of brain activity for semantic judgement was largely dependent on the proficiency level whereas AoA mainly affected the cortical representation of grammatical processes. The authors concluded that their findings support the view that both AoA and proficiency affect the neural substrates of second language processing, with a differential effect on grammar and semantics. For a detailed review of the role of AoA and proficiency on bilingual language processing and control see sections 1.5.1 and 1.5.2.

The term *critical period* was first used in research in embryology. Spemann (1938) showed that embryonic cells transplanted before (but not after) a certain stage of development are induced, by influences in their new cellular environment to develop like cells typical of the new site, not as they would have developed at their original site. Importantly, different criteria have been proposed for defining the notion of the critical period, among them identifiable beginning point and endpoint, short period of time and irreversibility when it is outside of the defined time window (which corresponds to the critical period). Later, in neurophysiological studies, Hubel and Wiesel (1963) were able to show that during the first weeks of postnatal development, in the Monkey and the Cat in particular, neurons of the primary visual cortex are sensitive to various environmental manipulations. Monocular deprivation, for example by eyelid suture of an eye, causes a great change of the binocular integration.

At the same time, some linguists interested in language acquisition and mostly defending the approach of the generative grammar introduced by Chomsky (1965) borrowed the concept of a critical period from embryology and neurophysiology. Thus, in linguistics from the 1950s and 1960s on, the term critical period was used under slightly varying definitions. One definition that is most closely tied to Lenneberg's (1967) original definition designates the critical period as the automatic acquisition from mere exposure that seems to disappear after this age, regardless of the exact nature of the underlying maturational causes (for a review, see DeKeyser & Larson-Hall, 2005). Some researchers postulated a less discontinuous and/or less absolute account, using, e.g., the terms *sensitive* or *optimal period* (for a review, see DeKeyser & Larson-Hall, 2005). Others again, explain maturational changes in language acquisition not by the presence of a critical or sensitive period but by interactional dynamics between the later acquired second language and the already consolidated first language (A. Hernandez, Li, & Macwhinney, 2005; P. Li et al., 2007; MacWhinney, 2012). However, whatever account is defended, evidence points towards fundamental maturational changes in certain aspects of memory and these neurodevelopmental aspects need to be taken into account in psycholinguistic research in order to provide accurate accounts of the mechanisms underlying second language acquisition and learning (DeKeyser & Larson-Hall, 2005).

1.2.1.1. THE *REVISED HIERARCHICAL MODEL* (RHM; KROLL & STEWART, 1994; KROLL ET AL., 2010) AT THE LEXICAL LEVEL

According to the *Revised Hierarchical Model* (RHM) by Kroll and Stewart (1994; Kroll et al., 2010), in late acquisition of an L2 lexicon, L2 lexical processing requires mediation via existing connections between translation equivalents in the L1 and the respective concepts, i.e. an internal representation or idea signified by a word (CNRTL, 2015b). Concerning connections between lemmas - i.e. the graphic form conventionally used as an address in a lexicon (CNRTL, 2015d) - in the two languages, there is a weak link from the L1 to the L2 translation equivalent but a strong link from the L2 to the L1 translation equivalent. Moreover, the links between L2 lemmas and concepts are weaker than the links between L1 lemmas and concepts, as can be seen in the schema depicted in Figure 1 (Kroll & Stewart, 1994; Kroll et al., 2010). However, with increasing proficiency and hence increasing automatization of the L2, direct links between L2 to the concept level will be established and mediation via the L1 translation equivalents becomes less involved (cf. The *Revised Hierarchical Model*; Kroll & Stewart, 1994; Kroll et al., 2010).

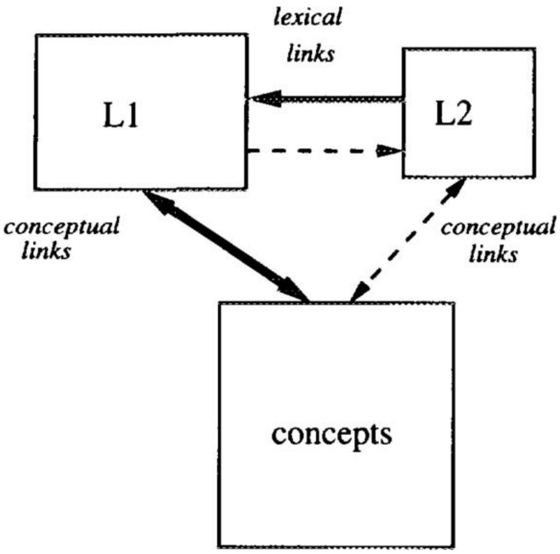

Figure 1. The *Revised Hierarchical Model* (RHM) of lexical and conceptual representation in bilingual memory (Kroll & Stewart, 1994). L1, first language; L2, second language. (Reprinted from Kroll & Stewart, 1994; copyright 1994; with permission from Elsevier)

The RHM is conceptualized as a model of language production but is less applicable to explain language comprehension (Kroll et al., 2010). Production and comprehension differ in terms of what is activated in the non-target language and the time course of processing. While production and comprehension may access the same lexicon, the events that initiate processing, and specific demands in speech planning, oral or written comprehension will determine the nature and sequence of the activated candidates. The RHM postulates that at the stage of low L2 proficiency, L2 processing differs from L1 processing, but with increasing L2 proficiency the L2 is becoming more automatized and L2 processing starts to resemble L1 processing. Neuroimaging data showing a 'convergence' between neuronal activation patterns in the L1 and L2, especially when L2 proficiency is high, support the predictions from the RHM model (Abutalebi & Green, 2007; see also sections 1.2.2 and 1.5.2). Moreover, the *Inhibitory Control* (IC) model (Green, 1998), which will be discussed in more detail in section 1.3.2.1, refers to the RHM in underlining that control processes are essential in bilingual language processing. Finally, Grainger, Midgley and Holcomb (2010) in the frame of the BIA-d (*Developmental Bilingual Interactive Activation Model*) model propose a developmental perspective of the *Bilingual Interactive Activation+* (BIA+) model (Dijkstra & van Heuven, 2002; cf. section 1.3.2.2), describing the transition from initial stages of second language acquisition as modeled by the RHM up to more balanced bilingualism, as modeled by the BIA+ model.

1.2.1.2. EMERGENTIST ACCOUNTS: THE *UNIFIED COMPETITION MODEL* (MACWHINNEY, 2008, 2012) AT THE SENTENCE LEVEL AND THE *DEVLEX MODEL* (P. LI ET AL., 2004, 2007) AT THE LEXICAL LEVEL

Emergentist approaches suppose that language acquisition is a highly experience-dependent process that is guided by the principles of Hebbian learning. These accounts postulate that cognitive modules emerge through processes such as competition or resonance (co-activation between neuronal substrates) but that they are not innate or constrained in their development by a critical period (cf. Bates, Bretherton, & Snyder, 1988; A. Hernandez et al., 2005). Emergentist accounts of first and second language acquisition, e.g. the *Unified Competition Model* (MacWhinney, 2008, 2012), postulate that it is not the presence of a critical or sensitive period that produces age of acquisition differences in second language learning. It is the dynamics of the interplay of *competition* (which is thought to arise whenever two cues for a given decision point in opposite directions), *parasitism* (the dependence of initial L2 lexical processing on L1 lexical processing, as described by Kroll and Stewart (1994)), *entrenchment* (a basic neurodevelopmental process of the increasing commitment of initially unspecialized neuronal substrate to the patterns of the first language), and *resonance* (a process that counteracts entrenchment in that it provides new encoding dimensions which allow for reconfiguring neuronal territory, permitting the successful encoding of L2 patterns) during the integration of the second language that lead to differential patterns of the relation between L1 and L2 lexica. On the neuronal level *resonance* designates the co-activation of the neuronal substrate of an already stored linguistic feature and the new feature that is to be encoded, and repeated recall and activation of this co-activation will consolidate the memory trace. With recurrent co-activation of the elements of one language and with repeated co-occurrence of environmental cues (e.g. individual speakers of a given language), the co-activation of elements of one language is reinforced while cross-language activation diminishes (‘resonance within emerging modules’; A. Hernandez et al., 2005). Similarly, the *DevLex model* (P. Li et al., 2004, 2007) is a self-organizing neural-network model of the development of the lexicon in children, explaining processes in both, comprehension and production. At the center of the model is a self-organizing, topography-preserving feature map of cortical organization (Kohonen, 1997). The model develops topographically organized representations for linguistic categories over time and takes into consideration how age of second language acquisition (L2 AoA) may affect the structure of the developing bilingual lexicon. In contrast with a classical ‘modularity of mind’ hypothesis (Fodor, 1983), supposing an inherently modular structure of the human mind, the DevLex model postulates that modules are not an inherent entity in the way the mind is structured, but on the contrary that via ‘emergent organization’ localized brain centers (and hence a degree of modularity) may arise as a function of ontogenetic developmental processes in interaction with the environment. The DevLex model aims at implementing a biologically and psychologically plausible model of language acquisition via self-organizing neural networks. Early plasticity in the emergent organization of linguistic categories and early competition between lexical representations and retrieval are crucial processes that play a role for the structure of the experience-dependent pattern of the bilingual lexicon. Moreover, concerning AoA effects, not only the degree of neuronal plasticity is a factor to be taken into account in order to explain different developmental patterns in the integration of a second language lexicon, but also stability in representation of previously acquired knowledge in order to avoid learned structures to be disrupted by new learning. The following AoA effects are conceptualized in these emergentist accounts. In the DevLex model, self-organization in simultaneous bilingual language acquisition is thought to lead to two separate lexica, one for each language, via the above-mentioned underlying principles of Hebbian learning and increasing resonance within emerging modules (i.e. language modules) and decreasing resonance between elements belonging to different modules. Hence, distinct and independent lexical representations emerge for each language. If, however, second language acquisition begins later, the child has already experienced years of consolidation and entrenchment, leading to progressively more automatic control of L1 in increasingly more committed neural substrates. Adult second (or further) language acquisition occurs against a background of an even more consolidated L1. Consequently, second language lexical representations will be learned as parasitic associates to L1 word forms and the L2 will not develop in the form of a topographically separate and independent L2 cluster, as it is hypothesized to be the case in simultaneous bilingual language acquisition (A. Hernandez et al., 2005). Li et al. (2004) propose that the topographical organization of the bilingual lexicon as proposed in the frame of the DevLex model may be reflected by the neuronal organization of language. Hernandez et al. (2005) suggest that the contrasting bilingual language biographies are reflected by a differential organization of the bilingual lexicon and that these differences should hence also be reflected by a differential organization at the neuronal level. However, these differences are not to be expected at the gross neuroanatomical level but rather at the level of "local cortical processing maps for audition, articulation, lexical form, sensory mappings, motor mappings, grammatical processes and sequential structures" or at the level of individual neurons (A. Hernandez et al., 2005, p. 222s). Finally, according to the DevLex model (P. Li et al., 2004) and the emergentist theory of competing modules in bilingualism (A. Hernandez et al., 2005), the role of control processes in adjusting the bilingual language use to linguistic and environmental constraints is the following. On the one hand, continued practice of the second language strengthens co-activation (‘resonance’) of the elements of the target language and weakens co-activation of elements belonging to the first and supposedly dominant language; this process is considered to be sufficient for refraining cross-language intrusions, especially those from a more dominant language (A. Hernandez et al., 2005). However, in code-switching as well as in translation from one language to another, further control processes are required, involving the coordination between inhibition and activation of the within- and cross-language co-activation. Moreover, and more importantly, it is crucial to improve our understanding of how strategic control of the two languages may be exerted and how control may be managed by the attentional system (A. Hernandez et al., 2005).

1.2.2. NEURONAL SUBSTRATE OF THE LEXICON AND GRAMMAR IN FIRST AND SECOND LANGUAGES

It is disputed if there is an integrated lexicon in bilingualism or if there are two functionally separated lexicons. Concerning the neuronal substrate of lexical representations, some evidence suggests largely shared L1 and L2 lexicons with overlapping (‘convergent’) neuronal activation (Fabbro, 2001; Ghazi Saidi et al., 2013; for reviews, see Abutalebi, 2008; Abutalebi & Green, 2007; Perani & Abutalebi, 2005), while some other evidence suggests the existence of separate lexicons (Gow, 2012). However, despite the overlap of neuronal activation in L1 and L2 processing, higher activation or more distributed activation patterns have repeatedly been reported for L2 as compared to L1 processing. In order to explain this pattern of shared and distinct activation in L1 and L2 processing, it has been suggested that L2 acquisition involves the same neuronal pathways as those engaged in L1 acquisition, whether the L2 is acquired early or late in life (Abutalebi, 2008). However, the observed activation of supplementary brain regions in L2 processing may reflect an additional requirement of attentional and control resources (for a review, see Abutalebi, 2008). Critically, mainly the factors L2 age of acquisition (see also, section 1.5.1), L2 proficiency (see also, section 1.5.2), or immersion in an L2 environment (see also, section 1.5.3) have been found to modulate the patterns of overlap and differences in the strength of neuronal activation in L1 and L2 processing (Abutalebi & Green, 2007; Indefrey, 2006).

In a review of neuroimaging studies of bilingual language representation and control, Abutalebi and Green (2007) show that there are convergent brain activity patterns for L1 and L2 especially in highly proficient bilinguals. Recently, neuroimaging techniques with very high spatial resolution, due to analysis methods such as multivoxel pattern analysis, have further corroborated the idea of a spatial overlap in neuronal L1 and L2 grammatical processing (Willms et al., 2011) and lexical processing (Buchweitz, Shinkareva, Mason, Mitchell, & Just, 2012). Willms et al. (2011) found that verb-specific regions showed indistinguishable activity patterns for English and Spanish, suggesting language-invariant bilingual processing for verbs. Buchweitz, Shinkareva, Mason, Mitchell and Just (2012) show that there is an identical multi-voxel pattern for the same noun across different languages (e.g. English: *hammer*, Portuguese: *martelo*). Furthermore, most of the existing evidence comprises group-wise analyses of fMRI data while individual-subject level analyses have become more popular only recently. There are some hints, that in bilinguals, individual-subject hemodynamical data may well show differences between L1 and L2 activation patterns (Indefrey, 2006). Thus, further advances in improving the spatial and temporal resolution respectively of neuroimaging and neurophysiological techniques might refine present theories of bilingual language acquisition, processing and control.

When now looking at the neuronal representation for different levels of linguistic processing separately, slight differences between L1 and L2 processing can be observed. Despite the wide overlap between lexical as well as grammatical processing in the L1 and L2, differences between early and late L2 acquisition have been observed especially for the neuronal representation of grammatical processes

(Fabbro, 2001; A. E. Hernandez, Hofmann, & Kotz, 2007; Wartenburger et al., 2003). In an fMRI study on syntactic processing, Kovelman, Baker and Petitto (2008) found differences in BOLD activation between the two languages of adult early Spanish-English bilinguals. Differences between the two languages were found in the left inferior frontal cortex (left IFC, BA 44/45) with increased activation for syntactically more complex (the degree of complexity was manipulated via word order) compared to less complex sentences in English, while no activation difference was found as a function of the similar variation of syntactic complexity in Spanish. This observation indicates that the manipulation of word order leads to syntactically more or less complex sentences in English while it does not substantially contribute to complexity modulations in Spanish. This finding is coherent with previous (psycho)linguistic observations that in Spanish, a romance language, speakers rely more on verb morphology than word order, while the reverse is true for English (Bates, 1999; Kail, Lemaire, & Lecacheur, 2012). In a study investigating the functional connectivity in syntactic processing in high and low proficient second language speakers, Dodel et al. (2005) found that areas classically found for syntax and language production, i.e. left inferior frontal gyrus, putamen, insula, precentral gyrus, supplementary motor area, are functionally more connected in the second as compared to the first language in syntactically more proficient bilinguals, which is not the case for lower proficient bilinguals. This result suggests that in more proficient bilinguals, specific functional connections are more developed compared to less proficient bilinguals during sentence production in L2. Moreover, proficiency has also been shown to affect neuronal activity patterns for semantic processing in the L1 and L2. That is, low proficient bilinguals showed more extensive cerebral activations during semantic judgment tasks than highly proficient bilinguals in Broca’s area (inferior frontal cortex, BA44) and the right middle frontal gyrus while highly proficient bilinguals showed greater activation in the left middle frontal and right fusiform gyrus compared to low proficient bilinguals (Wartenburger et al., 2003). Moreover, in this study AoA was found to mainly affect the cortical representation of grammatical processes, with late bilinguals showing more extensive activation in Broca’s area and subcortical structures in L2 than L1 grammatical processing, which was not the case in early bilinguals (Wartenburger et al., 2003). To sum up, despite a robustly observed overlap of the neuronal activation in L1 and L2 processing, there seem to be different neuronal representations of languages depending on some of their linguistic characteristics. Moreover, AoA and proficiency are crucial factors to account for variability in neuronal activation patterns in the L1 and L2.

It is to be stated, however, that independent of the integrated or separated nature of the bilingual lexicon, there is a wide consensus that both languages are activated in parallel (lexical access is non-selective in nature), even if only one language is the target language in a given context (Brysbaert, 2003; Dijkstra, 2005; Dijkstra & van Heuven, 2002; Hoshino & Thierry, 2011; Martín, Macizo, & Bajo, 2010; Van Heuven et al., 1998). Language non-selective access does not only seem to be the case for lexical access in visual word recognition but also for auditory comprehension, even though speakers are sensitive for sub-lexical cues (Dijkstra & van Heuven, 2002; P. Li, 1996; Marian & Spivey, 1999); moreover, language non-selective lexical access has also been found for language production (Starreveld, De Groot, Rossmark, & Van Hell, 2014). Kroll et al. (2010) argue that for the RHM, it is the phenomenon of parallel language activation that plays a crucial role, less so the question if the two languages are represented in one integrated lexicon or in contrast in separate lexica. Given that the co-activation of both languages, e.g. lexical representations or syntactic structures, (and also other sources of information like phonology and morphology) in both languages can cause cross-language competition and interference, control mechanisms over bilingual language use play a determining role in order to allow for successful multiple language use. The control mechanisms and processes over multiple language use will be addressed in the following section.

1.3. LANGUAGE CONTROL

Theoretical accounts on language control in bi- or multilingualism will be elaborated in section 1.3.2, and will be preceded by a section on language control in the native language (section 1.3.1). This comparison should help understanding the specificity of multiple language control and its qualitative and/or quantitative differences with general, or native, language control.

1.3.1. LANGUAGE CONTROL IN THE NATIVE LANGUAGE

Executive function (EF) involvement in language processing has been studied in the past but a lot remains to be learned about the exact role of EFs in specific language processes, such as in lexical or syntactic processing and especially when these language processes involve high working memory load or conflicting or ambiguous information. Moreover, to date little is known about the impact of typological differences of languages on the functioning of control mechanisms. In the native language, conflicts and interferences can occur at different levels of processing, i.e. for semantics (e.g. semantic conflict, Brier et al., 2010; semantic ambiguity, Rodd, Johnsrude, & Davis, 2010), syntax (e.g. syntactic ambiguity, January et al., 2009), phonology and phonetics (e.g. tongue twisters, Acheson & Hagoort, 2014) or between these levels (e.g. syntactic-semantic conflict, Thothathiri, Kim, Trueswell, & Thompson-Schill, 2012). Different neurocognitive models of language processing have tackled the issue of the involvement of domain-general executive control in language processing, e.g. Fedorenko and Thompson-Schill (2014), or in the *Memory Unification Control* (MUC) model proposed by Hagoort (2005, 2014). According to the MUC model, control processes are reflected by activation in the prefrontal cortex and the ACC, amongst others (Hagoort, 2005, 2014). Furthermore, in this model, Broca's region (inferior frontal cortex, BA 44 and 45) is not language-specific but realizes its language-relevant unification function in connection to language-relevant areas in temporal and inferior parietal cortex. Similarly, Fedorenko and Thompson-Schill (2014) strongly consider the involvement of domain-general executive control – the neuronal underpinnings of which involve prefrontal, inferior frontal and parietal regions - in L1 language processing. According to the model formulated by Fedorenko and Thompson-Schill (2014), the language network plausibly includes a functionally specialized core (brain regions that co-activate with each other during language processing) and domain-general periphery (a set of brain regions that may co-activate with the language core regions at some times but with other specialized systems at other times, depending on task demands). Evidence for executive function involvement in L1 language processing, with activation in, amongst others, inferior frontal, prefrontal, premotor or parietal areas, at different levels of language processing can also been found in an extensive review on neuroimaging studies of language processing (Price, 2012). Furthermore, there is evidence that the need of control involvement in L1 language processing varies over the lifespan. Older adults seem to employ different strategies in processing complex morphosyntactic information as compared to young adults, i.e. a shift from strong reliance on morphological cues to detect ungrammatical sentences towards a stronger reliance on contextual information. This strategy shift in language processing may reflect adaptive processes that take place during aging in order to compensate for decreased language and memory processing resources (Kail et al., 2012) which may be associated with changed control demands.

Finally, there are also other theoretical accounts dealing with control in language processing which suggest that there are no separate control instances involved in language comprehension, but that competition is resolved via lateral excitatory and inhibitory connections between co-activated nodes (cf. the TRACE model of speech perception by McClelland and Elman (1986)). Moreover, beyond monolingual language use, individuals mastering more than one language experience increased and specific control demands (Blumenfeld & Marian, 2013). The focus of the present doctoral thesis lies on the dynamics of executive control involvement in bilingualism and in the following section, an outline of neurocognitive models of bilingual language processing and control will be given.

1.3.2. LANGUAGE CONTROL IN MULTIPLE LANGUAGE USE

Long-term activity-dependent neuronal and cognitive changes in developing bilingualism have been discussed not only to involve adaptive changes in the language system but equally in cognitive control capacity and its underlying neuronal substrate. It is now widely accepted that in bilinguals both languages are activated even if a given context requires the use of only one specific language (Brysbaert, 2003; Dijkstra, 2005; Hoshino & Thierry, 2011; Van Heuven et al., 1998). As a direct consequence of the co-activation of multiple languages, control processes are required in order to successfully control cross-language interferences (Blumenfeld & Marian, 2013; Costa, Albareda, et al., 2008; Runnqvist et al., 2012), to adapt to a given interactional context (note that the following different types of bilingual interactional contexts have been suggested previously: *single language contexts* in which only one language is of use, *dual language contexts* in which two languages are used but in strict separation and with different interlocutors, and *dense code-switching contexts* in which languages are mixed even within single utterances; Green & Abutalebi, 2013). It has been suggested that domain-general executive functions are involved in controlling multiple language use (Green, 1998; Green & Abutalebi, 2013). This idea was corroborated by various empirical evidence (Gathercole et al., 2010; Hernández, Costa, Fuentes, Vivas, & Sebastián-Gallés, 2010; Kovacs & Mehler, 2009; Kroll & Bialystok, 2013; Prior & MacWhinney, 2010; for reviews, see Costa et al., 2009; Hilchey and Klein, 2011; Kroll and Bialystok, 2013; Valian, 2015). Different models have been proposed to account for control over multiple language use, amongst which four accounts will be presented here: (1) the *Adaptive Control Hypothesis* (Green & Abutalebi, 2013) - preceded by the *Inhibitory Control Model* (Green, 1998; section 1.3.2.1), (2) the *Bilingual Interactive Activation+* (BIA+) model (Dijkstra & van Heuven, 2002; Van Heuven et al., 1998; section 1.3.2.2), (3) the model of lexical access proposed by Costa, Miozzo and Caramazza (1999) / Costa (2005; section 1.3.2.4), and (4) the neurobiological framework of how bilingual experience improves executive function by Stocco, Yamasaki, Natalenko and Prat (2014; section 1.3.2.5). Empirical evidence on bilingual language control and the involvement of domain-general control processes in bilingual language control can be found in section 1.3.3.

1.3.2.1. THE *INHIBITORY CONTROL* (IC) MODEL (GREEN, 1998) AND THE *ADAPTIVE CONTROL HYPOTHESIS* (GREEN & ABUTALEBI, 2013)

The *Inhibitory Control* (IC) model (Green, 1998) describes the control of language processing in bilinguals. A basic assumption underlying the IC model is that there is a language non-selective access, which means that both languages of a bilingual are simultaneously activated but at varying degrees, and even if only one language is needed in a given context. The IC model involves multiple levels of control, which exert their regulatory function via both, external (bottom-up/exogenous) and internal (top-down/endogenous) control. One assumption of the IC model is that it considers language as a form of communicative action, and in realizing communicative actions, *task schemas* play a central role. One important level of control is localized at the level of these task schemas, which compete for output. The term *task schema* designates mental devices or networks that individuals may construct or adapt in order to achieve a specific task, with task schemas being involved in automatic as well as in controlled processes. Language task schemas are instances that are external to the language network and they are activated for executing a specific linguistic task (e.g. to produce a word) and they activate linguistic elements that are relevant for this task but suppress competitors that are irrelevant to the task. Task schemas are required in both, mono- and bilingual language use, but in bilingualism there is the additional requirement that a target language needs to be selected for realizing a linguistic goal and any non-target language needs to be suppressed. In unbalanced bilinguals, the L1 is supposed to have a higher level of resting state activation compared to the L2 and hence the L1 requires stronger inhibition in the case of L2 processing than vice versa. The locus of word selection is the lemma level (Levelt, Roelofs, & Meyer, 1999) and lemmas are considered to carry language tags that allow their selection or suppression according to the appropriateness of the use of a language in a given interactional context. This process of language control on the lemma level is inhibitory and reactive. On a superior level, control is exerted by the supervisory attentional system (SAS) – a domain-general control instance with its neuronal underpinnings essentially in the frontal lobes – which controls the activation, selection and maintenance of task schemas in case of controlled processes for which automatic control is not sufficient at the task schema level. The SAS constructs and modifies existing schemas as well as monitors their performance with respect to task goals. A language task schema then regulates the outputs from the lexico-semantic system by controlling the activation levels of representations within that system and by inhibiting inappropriate outputs from the system. To sum up, according to the IC model there are two main levels of inhibitory control in bilingual language processing, that is schema level inhibition and (language) tag inhibition in the bilingual lexico-semantic system. Moreover, in language switching, inhibiting a previously active schema and overcoming of the inhibition of a previously irrelevant language are costly processes that will lead to switch costs in comprehension and production, and these switch costs are supposed to be larger when switching into a more dominant and hence previously more strongly suppressed language, which means the mother tongue (L1) in unbalanced bilinguals (Green, 1998). Concerning the specific control processes as well as their neuronal substrate involved in bilingual language control, more recent publications, especially Abutalebi and Green (2007) as well as Green and Abutalebi (2013) give further insight, which can be seen as follows.

In the *Adaptive Control Hypothesis* by Green and Abutalebi (2013), one of the basic assumptions is that the initial co-activation of languages necessitates top-down control in order to avoid cross-language interferences. These control processes are partly realized by the involvement of domain-general cognitive control, that means processes of control shared by different domains (see also, Abutalebi & Green, 2007). It is supposed that bilinguals regularly using a foreign language request their control processes more intensely than individuals using less regularly a foreign language (i.e. the so-called monolinguals). Consequently, one may suppose that bilingualism has a training effect on domain-general cognitive control. In the *Adaptive Control Hypothesis*, a set of eight distinct control processes is postulated to play a role in the control over a bilingual's languages: *goal maintenance*, *interference control* - including *conflict monitoring* and *interference suppression* -, *salient cue detection*, *selective response inhibition*, *task disengagement*, *task engagement* and *opportunistic planning*. The neuronal language control network assumed to underlie these different control processes - especially in language production - involves the following areas, accompanied by the mention of their assumed cognitive function (Figure 2; for a quantitative meta-analysis, see Luk, Green, Abutalebi, & Grady, 2012): the anterior cingulate cortex (ACC; conflict monitoring) and the pre-supplementary motor area (pre-SMA; conflict monitoring, initiating speech in language switching); left prefrontal and inferior frontal cortex (control of interference), parietal cortical areas (maintenance of task representations) and the caudate nucleus (switching between languages). Moreover, the model involves reciprocal connections between basal ganglia structures and the cerebellum.

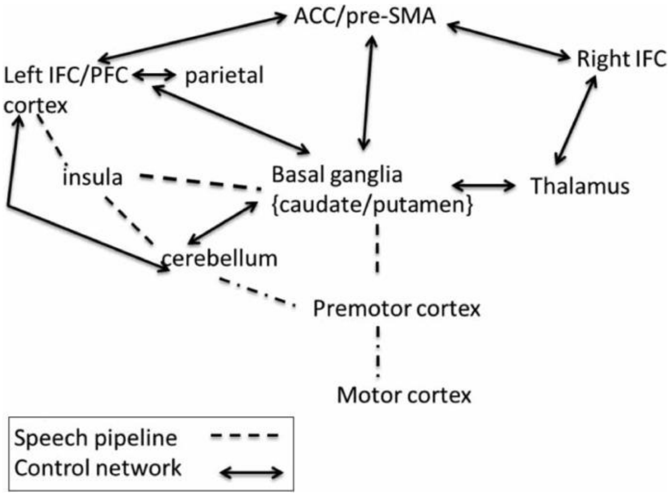

Figure 2. The simplified language control network and speech production regions (Green & Abutalebi, 2013). In the *Adaptive Control Hypothesis*, the interplay between the different nodes in the neuronal language control network as a function of specific control demands guarantees successful adaptation to a given interactional context. ACC, anterior cingulate cortex; IFC, inferior frontal cortex; PFC, prefrontal cortex; pre-SMA, pre-supplementary motor area.

The adaptation of the interplay between the different areas in the neuronal language control network as a function of specific control demands in order to guarantee successful adaptation to a given interactional context is a core feature in the *Adaptive Control Hypothesis*. That means, in interactional contexts with a close contact of languages and therefore a concrete risk of cross-language grammatical competitions, it is assumed that some control processes such as interference suppression would have a higher weight. Finally, the study of control of multiple language use should take into consideration the complex interplay between inhibition and activation of languages. The neurocognitive processes underlying language comprehension and production depend on the degree of balanced dominance between the languages (Peltola, Tamminen, Toivonen, Kujala, & Näätänen, 2012) or on language proficiency (Abutalebi, 2008; Videsott et al., 2010). A further observation corroborating this point and to be taken in account in an hypothesis of *adaptive control* is the probably important role of language context in modulating language activation (Wu & Thierry, 2010).

According to the *Adaptive Control Hypothesis* three interactional contexts are distinguished: *single language contexts* (only one language is used in a given context among all interlocutors; a code-switch may however occur when the context is changed, which is the case for instance if one language is used at work and another language at home), *dual language contexts* (languages are switched when different interlocutors are addressed; however, no code-switches occur within utterances), and the *contexts of frequent code-switching* (various forms of code-switching within utterances occur). These different interactional contexts pose varying constraints on bilinguals. The interactional context determines how task schemas are coordinated, i.e. which control processes are required for a successful linguistic interaction (Green & Abutalebi, 2013). To sum up, according to the *Adaptive Control Hypothesis* (Green & Abutalebi, 2013), bilingual language use and the specific involved control processes adapt interdependently. That is, every type of bilingual may use specific control processes more than others according to the way the two languages are separated or mixed (*interactional context*) and consequently, these control processes become strengthened. This raises the question of (1) which control processes could benefit from bilingualism, and (2) which linguistic or non-linguistic factors in bilingualism may cause a bilingual advantage, given the multi-factorial nature of bilingualism itself (Luk & Bialystok, 2013).

Recently, a lot of attention has been drawn to the role of the basal ganglia in bilingual language control. Much insight has since then been gained especially on the role of the left caudate in language switching (Abutalebi, Rosa, et al., 2013; Crinion et al., 2006). Moreover, also the left putamen was found to be important in language control (Abutalebi, Rosa, et al., 2013) which has been speculated to be due to the specific demand in motor programming of L2 in bilinguals (Chan et al., 2008; Garbin et al., 2010). Furthermore, it has been observed that basal ganglia activity (i.e. left putamen) during non-native language processing depends on the degree of proficiency in that language, with lower proficiency being associated with stronger activity in the left putamen (Abutalebi, Rosa, et al., 2013). On the other hand, activity levels in the caudate-fusiform circuit have also been shown to predict the success in acquiring non-native reading skills, which is thought to be due to the control function exerted by these neuronal regions (Tan et al., 2011). Basal ganglia impairments due to lesions or degenerative illnesses, such as Parkinson's diseases, Huntington's disease, have been found to particularly affect syntax (rule-based knowledge) and other rule-based automatisms and procedural memory, but less so semantics, which has been shown to be mainly stored in cortical regions (Stocco et al., 2014); cf. the declarative/procedural model of language by Ullman (2001a). However, in a study on language processing in patients with basal ganglia dysfunction, Longworth (2005) failed to find systematic impairments of syntactic processing, but observed difficulties in suppressing competing alternatives. This finding is consistent with findings of the implication of basal ganglia in suppressing competing alternatives (Abutalebi, Rosa, et al., 2013; Stocco et al., 2014) and language switching. To sum up, main functions of the basal ganglia in language comprehension and production seem to be (1) monitoring of syntax, (2) suppression of interfering semantic and syntactic competitors as well as (3) bilingual language selection and switching. For an account focusing on the role of basal ganglia function in bilingual language control, see Stocco et al. (2014), section 1.3.2.4.

1.3.2.2. THE *BILINGUAL INTERACTIVE ACTIVATION+* (BIA+) MODEL (DIJKSTRA & VAN HEUVEN, 2002)

The *Bilingual Interactive Activation+* (BIA+) model is conceptualized as a model of bilingual word recognition and shares the basic architecture of the monolingual *Interactive Activation* model (McClelland & Rumelhart, 1981). A basic assumption underlying the BIA+ is that there is a language non-selective access, which means that both languages of a bilingual are activated at varying degrees, even if only one language is the target language in a given interactional context. L1 lexical representations have in general higher resting level activation than those of the L2 and given that L2 representations are on average of a lower subjective frequency than L1 representations, they are activated more slowly than L1 representations ("temporal delay assumption"). Moreover, it is assumed that the bilingual mental lexicon is integrated across languages, which means there is one lexicon containing the words of the different languages. As a direct consequence, in an integrated lexicon with language non-selective access co-activated representations from both languages compete for recognition. In an interactive activation framework (McClelland & Rumelhart, 1981), inhibitory connections between words from different languages would be expected in the frame of the integrated lexicon hypothesis, while for the separate lexica hypothesis, inhibitory connections would only be expected between words of the same language (Van Heuven et al., 1998). Within-level inhibition (lateral inhibition) as well as top-down inhibitory control from language nodes allows for the selection of the correct target word in the target language. This means that in the BIA+ model, late language selection is implemented via a top-down inhibitory mechanism that allows the selection of the target element amongst non-language-selectively co-activated potential targets. The BIA+ model is also strongly inspired by the IC model (Green, 1998), as for instance reflected by the inclusion of task schemas and task control in the BIA+ model; this produces the architecture of the BIA+ model with a distinction between a word identification system and a task/decision system. The task/decision mechanism dynamically evaluates the perceived activation in different parts of the identification system and links it to a particular response in such a way as to produce the best possible performance. It is only possible to adapt performance by exerting control over the task/decision mechanism but not by adapting the activation level of individual items or languages. Hence, only a certain degree of control over performance is possible, for instance via selective read-out or dynamic adjustment of identification criteria. The linguistic context (e.g. sentence context) can directly affect the activity in the word identification system, while the non-linguistic context (e.g. participant strategies) can only affect the task/decision system.

In the BIA+ model, the selection by language operates via top-down control in selectively enhancing the processing of representations in one language and/or inhibiting those in the other language. Language-specific selection functions via the degree of activation of language nodes for each language. In the BIA+ model, language control processes are implemented via the language node: both, top-down activation or maintenance of language node activation (endogenous control) as well as automatic bottom-up activation of language nodes via lexical representations and the subsequent inhibition of lexical representations by language nodes (exogenous control) operate via the language node. To sum up, the BIA+ model postulates that bilingual language processing is initially language non-selective. This initial phase is followed by rapid convergence on the appropriate language-specific representation. The selection of the target representation in the target language involves both top-down and within- as well as cross-language lateral inhibitory mechanisms.

Moreover, in the form of the BIA-d model, Grainger et al. (2010) point out the developmental aspects of the BIA+ model. Departing from the *Revised Hierarchical Model* (RHM; Kroll et al., 2010)

Grainger et al. consider how the representation of and the link between L1 and L2 in an integrated lexicon evolve from the L2 learner to the highly proficient late bilingual, hence how L1-L2 connectivity evolves from an initial RHM into the BIA+ model. At the initial stage in the *Interactive Activation* model, each word form in L1 is linked via mutually excitatory connections to certain semantic features and word forms that are co-activated by the same stimulus (orthographically or phonologically similar words) while those that are semantically incompatible have mutually inhibitory connections (cf. McClelland & Rumelhart, 1981). According to the RHM, late L2 learners first establish links to the translation equivalents in their L1. With increasing L2 knowledge the links between translation equivalents become strengthened but direct links between L2 lexical representations and semantic representations (concepts) start to establish. With further increasing proficiency, the direct links between the L2 lexical representations and the concept level are further strengthened and the links between translation equivalents are qualitatively changed, which is probably linked to improved control over L2 language activation that starts to become necessary with increasing L2 proficiency. Connections between the L2 word form and the semantic features and the L2 tag continue to be reinforced via Hebbian learning and clamping the L1 translate is less and less required. This shift towards L2 autonomy is reinforced by the development of top-down inhibition from the L2 language node to the L1 translation equivalent. The increasing L2 language node activation reinforces this inhibitory link while the excitatory links between L1 and L2 lexical representations become weakened. Moreover, there is evidence that immersion in an L2 environment may be critical for developing inhibitory control over cross-language interference from L1 (Linck, Kroll, & Sunderman, 2009), which is an important issue when considering the role of language learning in classroom vs. natural contexts. Hence, according to the BIA-d model late L2 learning (classroom learning) consists of two largely overlapping phases, an earlier supervised (i.e. mapping of L2 lexical representations to their L1 translation equivalents) and a later non-supervised stage (i.e. when L1 translates cease being clamped and L2 autonomy begins to increase). To sum up, according to the BIA-d model (Grainger et al., 2010), sustained exposure to the L2 leads to a gradual integration of L2 lexical representations into an integrated lexicon, which is characterized by between and across language connectivity and which also increases cross-language interference. With sustained L2 exposure and following the principles of Hebbian learning, a shift towards L2 autonomy develops mainly due to the reinforcement of excitatory connections between the L2 word forms and semantic features as well as the development of inhibitory connections between the L2 language node and L1 lexical representations. More precisely, the following developmental changes are hypothesized to occur: excitatory connections between L2 lexical representations and semantics at the conceptual level increase, inhibitory connections between the L2 language node to L1 lexical representations increase, excitatory connections between L2 lexical representations and their translation equivalents in the L1 first increase and then decrease when the inhibitory connections from the L2 language node become stronger, and inhibitory connections develop between L2 lexical representations and orthographically similar words in L2 and L1. These processes in the BIA-d model lead from initial L2 learning, modeled by the RHM, to quite high L2 proficiency and L2 autonomy, modeled by the BIA+ model.

1.3.2.3. IC VS. BIA+ MODELS IN COMPARISON

It has been claimed, that the *Inhibitory Control* (IC) model (Green, 1998) and the *Bilingual Interactive Activation+* (BIA+) model (Dijkstra & van Heuven, 2002) are rather complementary, with the IC model focusing on the task schema level and on bilingual language production and the BIA+ model being centered on the bilingual lexico-semantic system and bilingual language comprehension (Dijkstra & van Heuven, 2002). Importantly, these two above-mentioned models as well as the *Inhibitory Control* (IC) model (Green, 1998) and its revisited version, i.e. the *Adaptive Control Hypothesis* (Green & Abutalebi, 2013) postulate an initial co-activation of languages which is thought to justify the involvement of control processes. Moreover, both the IC and the BIA+ models assume that there is an interplay between (1) activation of lexical candidates or lemmas in the two languages and (2) adaptation of the decision criteria implying top-down inhibition (Dijkstra & van Heuven, 2002).

1.3.2.4. THE MODEL OF LEXICAL ACCESS COSTA ET AL. (1999) / COSTA (2005)

Further theoretical accounts have been proposed that argue in favor of a complex interplay between control (amongst others inhibition) and activation to explain bilingual language selection and inhibition. Costa et al. (1999) suggest, that the semantic system co-activates the lexicons of both languages but only the lexical nodes of the target language are then considered for selection. Moreover, nonlexical (or nonsemantic) orthography-to-phonology (grapheme to phoneme) conversion mechanisms are to be considered in this model in order to account for nonsemantic cross-language interference and facilitation effects, which have been found at the phonological level. According to this theoretical account, control involvement in bilingual language use may depend on the proficiency level in the second language (Costa, Santesteban, & Ivanova, 2006); there is empirical evidence that activation in the neuronal control network is more strongly involved in low proficient bilinguals compared to highly proficient bilinguals (Abutalebi & Green, 2007; see also, section 1.5.2). Costa and collaborators suggested that a different control mechanism is used by highly as compared to low proficient bilinguals (Costa & Santesteban, 2004; Costa et al., 2006). Accordingly, in highly proficient bilinguals, lexical selection operates via a language-specific selection mechanism, that means the second language is sufficiently active for allowing the words of the L2 to reach a sufficient activation level compared to the words of the L1; in contrast, in low proficient bilinguals, lexical selection requires the involvement of inhibitory control (Costa, 2005). Empirical evidence also suggests, that in highly proficient bilinguals, neither linguistic similarity between the two languages nor the age of acquisition of the second language affect lexical selection performance, whereas in low proficient bilinguals these two factors do play a role (Costa et al., 2006). Nevertheless, in some specific demanding situations, for instance when an additional L3 or L4 mastered at very low proficiency is used, inhibitory control has to be involved even in *highly* proficient bilinguals. Furthermore, it is suggested that highly proficient bilinguals who have developed a language-specific selection mechanism are also capable of setting different selection thresholds for their languages which allows the selection of the weakest language in case of code-switching. One further claim concerning inhibitory control in this theoretical account is that inhibitory control over languages affects the non-target language as a whole but the empirical evidence does not allow to entirely dismiss the claim that selection would take place at the level of individual lexical representations (Costa & Santesteban, 2004; Costa et al., 2006). Finally, in a more recent study, conflict monitoring is suggested to be one of the crucial domain-general control processes involved in bilingual language processing, however its involvement depends on the conversational demands of the type of bilingual interactions (Costa et al., 2009). Hence, if the linguistic environment imposes strong monitoring which language to produce in each communicative interaction, a bilingual advantage on this domain-general control process may emerge in the long run. If the environment does however, require less monitoring, it may not benefit from training. The relation between monitoring and conflict resolution (involving inhibitory control) is however not specified and requires further investigation. To sum up, it is suggested that domain-general executive control is involved in multiple language control but that the type and degree of control depends on the characteristics of the bilingual individual, i.e. inhibitory control is required mainly by low proficient but less so by highly proficient bilinguals and the involvement of conflict monitoring depends on the bilingual linguistic environment.

1.3.2.5. THE NEUROBIOLOGICAL FRAMEWORK ON BILINGUAL LANGUAGE CONTROL BY STOCCO ET AL. (2014)

According to Stocco et al. (2014) – who adapt the *Conditional Routing Model* (Stocco, Lebiere, & Anderson, 2010) to bilingual language control -, the basal ganglia, and in particular the striatum, are a central locus for bilingual language control. The basal ganglia, i.e. a subcortical brain region, are a concentration of gray matter where input from all over the cortex is received and output - especially and amongst others - to the PFC takes place. Inhibitory processes within the basal ganglia control the output connections and, by doing so, control the information transmitted to the PFC. In bilinguals, we might thus want to look for higher efficiency of basal ganglia control processes. An underlying idea to this theoretical approach is the inscription of language in a memory framework, with lexical entries and semantics being stored in the declarative memory and syntax being stored in the procedural memory. Semantic processing requires the activation of a neuronal network underlying declarative memory – cortical structures mainly in the temporal and inferior frontal cortex - and syntactic processing (complex linguistic rules) the network for procedural memory – the basal ganglia circuit - (Stocco et al., 2014); cf. the declarative/procedural model of language by Ullman (2001a) as well as Paradis (2004). According to the *Conditional Routing Model* (Stocco et al., 2010), "with learning, grammatical rules become permanently stored in the basal ganglia in the form of patterns of synaptic strengths that determine signal routing". With practice, rules become encoded in abstract form in the basal ganglia and can be applied whether a cortical conscious representation of this rule is encoded or not. In emerging bilingualism, when syntactic processes are getting more automatic with increasing L2 proficiency its competition for production is also getting stronger and thus increased basal ganglia activity is necessary in order to control the connection strengths in either of the languages. Due to the permanent constraint to keep the two languages apart and to effectuate language switches when necessary, the ability of the basal ganglia to exert control over cortico-cortical connections, and to flexibly reroute the signal flow to the frontal cortex, becomes strengthened. Critically, according to

Stocco et al. (2014), bilinguals show a ‘top-down bias’ which means that bilingual practice leads to strengthened striato-cortical connections (‘endogenous control’, ‘top-down attentional processes’), which exert control over cortico-cortical connections (‘exogenous control’, ‘bottom-up attentional processes’). This bilingual top-down bias is thought to lead to overall faster processing, to an advantage in task switching, to a better capacity in selecting an appropriate rule and in overriding habitual but inappropriate rules. However, the bilingual top-down bias may also lead to a reduced reactivity to sudden contextual or perceptual changes in the outside world that require immediate changes of behavior (bottom-up attentional processes). It is important to note, that Stocco et al. (2014) consider that the control exerted by the basal ganglia is realized not by inhibiting irrelevant rules but by selecting appropriate rules and overriding habitual but inappropriate rules. Apart from mediating syntactic rules inscribed in procedural memory connections, the basal ganglia play a crucial role in language switching, as it has been observed in healthy populations (Crinion et al., 2006; Garbin et al., 2011) or in intra-operative electrical stimulation (X. Wang, Wang, Jiang, Wang, & Wu, 2013). Moreover, in patients suffering from impairment of basal ganglia function, such as in Parkinson’s disease, Huntington’s disease or due to lesions, syntax (rule-based knowledge) and other rule-based automatisms and procedural memory as well as language switching have been found to be particularly affected (Abutalebi, Miozzo, & Cappa, 2000; Green, 2008; Paradis, 2008; Stocco et al., 2014). However, in a study on language processing in patients with basal ganglia dysfunction, Longworth (2005) observed impairments in suppressing competing alternatives but less so in syntactic processing. This finding is consistent with findings of the implication of basal ganglia in suppressing competing alternatives (Abutalebi, Rosa, et al., 2013; Stocco et al., 2014) and language switching (Crinion et al., 2006; Fabbro, 2001; Stocco et al., 2014). To sum up, main functions of the basal ganglia in language comprehension and production may be (1) monitoring of syntax, (2) suppression of interfering semantic and syntactic competitors as well as (3) bilingual language selection and switching (Stocco et al., 2014). In a recent review, Aron, Robbins and Poldrack (2014) claim that the inhibition of response tendencies is reflected by activity in the right inferior frontal cortex (rIFC) together with a fronto-basal-ganglia network. This idea is consistent with the finding that cortico-subcortical connections/projections, especially between the PFC and the striatum, play an important role in control over language processes. Moreover, the observation of an overlap of domain-general and language control networks - and especially the shared involvement of basal ganglia activity - corroborates the idea that domain-general executive control is involved in and trained by multiple language use.

1.3.3. EMPIRICAL OBSERVATIONS ON CONTROL PROCESSES IN BILINGUAL LANGUAGE PROCESSING

One of the key discoveries in human cognitive and brain sciences in the past 20 years is the increasing evidence from behavioral, neurophysiological and neuroimaging studies for the plasticity of executive functions. Executive functions can become more efficient in all age ranges by engaging in certain activities requiring attention as well as memorization and control over complex processes (A. Diamond, 2011, 2013; for a closer look on the genetic part in executive function efficiency, see e.g. Friedman et al., 2008). Different environmental factors also affect the efficiency of executive control processes. It has been shown that critical factors for developing executive control mechanisms are, for instance, multiple language use (for reviews, see Bialystok et al., 2012; Costa et al., 2009; J. Diamond, 2010; Kroll & Bialystok, 2013; Kroll et al., 2012; Luk & Bialystok, 2013; Tao et al., 2011; Valian, 2015), expertise in music (Bialystok & DePape, 2009), video game playing (Bavelier & Davidson, 2013; Dye, Green, & Bavelier, 2009), and actively performing sports requiring high bimanual coordination (A. Diamond & Lee, 2011; for a review, see A. Diamond, 2011). Interestingly, an activity-dependent improvement of executive function efficiency has been observed particularly in age groups usually showing a lower capacity of executive functions (for the rise and fall of executive function capacity over lifespan, see Zelazo, Craik, & Booth, 2004), i.e. children (Bialystok & Martin, 2004; A. Diamond & Lee, 2011; Moutier, Angeard, & Houdé, 2002) and older individuals (Bialystok, 2007; Bialystok, Craik, & Luk, 2008; Grant, Dennis, & Li, 2014; Luk, Bialystok, Craik, & Grady, 2011; Valian, 2015), but not for young adults possibly due to an optimal efficiency of the executive functions in this age group (Craik & Bialystok, 2006). In the following sections, behavioral, neurophysiological and neuroimaging evidence of domain-general control involvement in bilingual language use will be presented.

1.3.3.1. BEHAVIORAL FINDINGS

A growing number of behavioral studies on control processes in bilingualism have used different experimental paradigms and tasks to test the hypothesis that domain-general control processes are involved in bilingual language control. The rationale of most of these studies was that the daily use of more than one language may be a critical factor for accounting for better control efficiency also in non-linguistic tasks. However, to date, combined empirical behavioral evidence does not provide a clear-cut picture. Whereas some studies show a bilingual executive processing advantage (Bialystok, 2006; Bialystok, Craik, & Ryan, 2006; Bialystok & DePape, 2009; Bialystok & Viswanathan, 2009; Costa, Hernández, & Sebastián-Gallés, 2008; Gathercole et al., 2010; Hernández et al., 2010; Kovacs & Mehler, 2009; Kuipers & Thierry, 2013; Luk & Bialystok, 2013; Marzecová et al., 2013; Prior & MacWhinney, 2010) a number of other studies do not demonstrate any bilingual advantage (Antón et al., 2014; Duñabeitia et al., 2014; Gathercole et al., 2014; Kousaie & Phillips, 2012a; Morton & Harper, 2007; Paap & Greenberg, 2013; for reviews, see e.g. Bialystok et al., 2012; Costa et al., 2009; Hilchey & Klein, 2011; Kroll & Bialystok, 2013; Tao et al., 2011).

Recent reviews on the bilingualism advantage on control processes have attempted to shed new light on these controversial findings in the literature (Costa et al., 2009; Hilchey & Klein, 2011; Kroll & Bialystok, 2013). Kroll and Bialystok (2013) argue that the use of multiple languages may be a critical factor for improving the efficiency of different executive functions, among them inhibition. This argument relies on the key discovery in psycholinguistics that both languages are active to some degree in bilingual individuals. Consequently, the joint activation of multiple languages requires the involvement of an executive control mechanism for managing the bidirectional persistent cross-language influences. Hilchey and Klein (2011), however, suggest that there are executive processes that seem to show a bilingual benefit, i.e. general executive processing and especially conflict monitoring, though not necessarily inhibition. Moreover, and more important, these authors claimed that the bilingual advantage on the interference effect (i.e. better performance in the incongruent condition than in the congruent one for bilinguals in comparison to monolinguals) is a sporadic phenomenon that can even disappear after practice. In contrast, as it is pointed out by Hilchey and Klein (2011), that bilinguals in many cases outperform monolinguals on both congruent and incongruent trials which supports accounts claiming an overall processing advantage and an advantage in (conflict) monitoring, however not the idea that specifically inhibitory control is involved in bilingual language control and hence benefits from a bilingual advantage (for a review specifically on behavioral, neurophysiological and neuroimaging findings concluding that there is no clear picture on which executive control processes actually are involved in bilingualism, see Hilchey & Klein, 2011). For instance, some studies found a bilingual advantage in conflict monitoring processes (Singh & Mishra, 2015), on both conflict monitoring and conflict resolution (involving inhibition; Costa et al., 2009; Costa, Hernández, et al., 2008), others reported an advantage in goal maintenance but not in reactive inhibition (inhibition of a distracting component of the stimulus; Colzato et al., 2008), and again other studies found evidence for a bilingual advantage specifically for inhibitory control processes (Bialystok et al., 2008; Kovács, 2009; Linck, Hoshino, & Kroll, 2008), or in cognitive flexibility (mental shifting; Marzecová et al., 2013; Prior & MacWhinney, 2010). In a modified antisaccade task, Bialystok, Craik and Ryan (2006) found that young and older adult bilinguals showed better performance on inhibitory control (or ‘interference suppression’) measures but that only older bilinguals also showed an advantage on switching (or ‘cognitive flexibility’) and response inhibition measures. In a study employing the same paradigm but testing bilingual children from two different cultural settings (Canada, India), Bialystok and Viswanathan (2009) found that both groups of bilingual children showed increased performance on inhibitory control (or ‘interference suppression’) and switching (or ‘cognitive flexibility’). However, bilingualism did not influence the performance of response suppression in this task. These observations suggest that activity-dependent long-term effects on executive function capacity vary over the lifespan and differ between the involved processes.

Concerning performance related to task- and language-switching, in a modified antisaccade task (note that the antisaccade task consists in reprogramming the automatic movement of the eyes toward a target in the opposite direction), a behavioral bilingual advantage on switching (or ‘cognitive flexibility’) measures has been found for bilingual children (Bialystok & Viswanathan, 2009) and older adult bilinguals, but not in young adult bilinguals (Bialystok et al., 2006). This suggests that a bilingual executive control advantage may emerge especially in age groups that in general manifest lower than optimal executive function performance, i.e. in children and older adults (Zelazo et al., 2004), rather than in young adults who are in general at peak performance. In a behavioral non-verbal task switching paradigm, Prior and MacWhinney (2010) also found a bilingual advantage for the switching effect (difference between switch and repetition trials within mixed blocks containing both switch and repetition trials) but not for the mixing effect (difference between repetition trials in mixed blocks compared to trials in non-mixed blocks). The bilingual advantage found for this task switching effect was interpreted to reflect higher efficiency of (1) reactivating the relevant rule and of (2) reconfiguring stimulus-response mappings according to the new rule. In a study using the same paradigm, bilinguals with a higher frequency of daily language switching showed reduced switching costs as compared to bilinguals with a lower frequency of daily language switching and monolinguals (Prior & Gollan, 2011). On the other hand, a bilingual advantage on switching performance is not consistently found (for a review, see Hernández et al., 2013) and there is also evidence for partially independent neurocognitive processes underlying linguistic and non-linguistic switching (ERP study; Magezi, Khateb, Mouthon, Spierer, & Annoni, 2012). However, different types of bilingualism may to varying degrees involve the control required for language switching or language inhibition (Green & Abutalebi, 2013; Green & Wei, 2014). Therefore, we need to more closely look at variables in the individual language biography before drawing firm conclusions. These findings suggest that there is an overlap between switching processes in linguistic and non-linguistic cognitive domains and that the efficiency of switching may depend on the frequency of daily language-switching.

Thus, on the one hand, some control processes seem to be involved in multiple language control – and thus benefit from daily practice – more than others. On the other hand, different profiles of bilingual language use may involve different control processes and hence lead to a different pattern of advantages in domain-general control processes. Therefore, we agree with Hilchey and Klein (2011) that a more holistic approach should be used to investigate the emergence of a bilingualism advantage on executive control processes. Similarly, Kroll and Bialystok (2013, p. 502) claimed that ‘tasks are not measures of inhibition or not’ and therefore also encourage a holistic approach in the study of the bilingual executive processing advantage. It is not unplausible that the cross-studies inconsistency observed in the literature with respect to the effect of bilingualism on executive functions may also be due to another methodological consideration. Indeed, bilingualism is not a categorical variable, and consequently, one should take into consideration the multi-dimensional characteristics of bilingualism (see also, section 1.5). Thus, statistical group analyses with bilingualism as a between-subjects factor is disputable as it leads to average data of individuals who are not always totally comparable in terms of both linguistic knowledge in and language use of the second language. Therefore, and we will come back later on this point in the present doctoral thesis, we consider as very relevant to approach the question of the impact of bilingualism on control processes using correlation and multiple regression analyses. To sum up, the formulation of a coherent answer to the question of the relationship between bilingualism and long-term cognitive advantages on executive control, and especially inhibition, from the cross-studies empirical evidence is a challenging task. Indeed, even in studies showing an advantage of bilingualism, there is no consensus on which processes are involved in bilingual language processing and hence may show a bilingualism advantage. Finally, behavioral measures can be adapted to examine executive function capacity in bilinguals and monolinguals, but neurophysiological and neuroimaging data can bring about more fine-grained information on the neuronal level, due to the high temporal resolution in the case of electroencephalography (EEG) or magnetoencephalography (MEG), and due to high spatial resolution in the case of functional magnetic resonance imaging (fMRI).

1.3.3.2. NEUROPHYSIOLOGICAL FINDINGS ON THE IMPACT OF BILINGUALISM ON EXECUTIVE CONTROL

Several previous studies have corroborated the potential of neurophysiological and neuroimaging techniques for detecting effects on a more fine-grained scale when behavioral methods reach their limits. For instance, in an ERP study examining the impact of bilingualism on interference suppression, using a Stroop, Simon and an Erikson flanker task, Kousaie and Phillips (2012b) did not find a behavioral advantage of bilingualism but their ERP data revealed group differences. In the Stroop task, monolinguals showed larger fronto-central N2 (time window 220 to 360 ms) amplitudes than bilinguals for all trial types, which was interpreted to reflect an advantage in conflict monitoring. The control N2 (or N200) component is a negative-going component peaking at around 200 ms after stimulus onset which is usually associated with conflict monitoring or inhibitory processes. Similarly, increased frontal N2 amplitudes were found in a Go/Nogo task in bilinguals compared to monolinguals (Fernandez, Tartar, Padron, & Acosta, 2013; Moreno, Wodniecka, Tays, Alain, & Bialystok, 2014).

Moreover, in a Simon task, Kousaie and Phillips (2012b) found that bilinguals showed smaller amplitude of the P3 than monolinguals. The P3 (or P300) component is a positive-going waveform at around 250-500 ms after stimulus onset with a centro-parietal distribution and a P3 effect is regularly found in tasks requiring inhibitory control. Given that a decreased P3 amplitude had previously been associated with increased resource allocation, this finding was interpreted not to corroborate the hypothesis of a bilingual advantage. Furthermore, in the Erikson flanker task the P3 (time window 300 to 500 ms) peaked later in monolinguals than in bilinguals which was interpreted to reflect slower stimulus categorization in incongruent trials in monolinguals compared to bilinguals (Kousaie & Phillips, 2012b). Kousaie & Phillips (2012b) also found differences for the Stroop P3[5] between monolinguals and bilinguals in that the general peak latency was later in monolinguals as compared to bilinguals. In an ERP study also using a Stroop task, Coderre and Van Heuven (2014) found a descriptively smaller N4 effect in bilinguals compared to monolinguals, which was interpreted to reflect an advantage in inhibitory control and proactive control over irrelevant information. The N4 (or N400) component is a negative-going component at posterior sites peaking at around 400 ms after stimulus onset, and effects on the N4 amplitude have been found to reflect linguistic and non-linguistic incongruency processing or inhibitory control processes. In an ERP study, testing the impact of 6-months early-stage L2 learning on the neuronal processing in a Go/Nogo task, Sullivan et al. (2014) found an increase of the positivity in the Nogo P3 post-L2 learning compared to pre-L2 learning in the L2 training group, a difference that was not present in a control group that did not participate in L2 training. This advantage was interpreted to reflect a training-induced strengthening of the neural network involved in response inhibition. Moreover, in a study relating pupil size with the N4 amplitude in the processing of semantically unrelated stimuli in toddlers, ERP evidence, i.e. a negative correlation

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[5] Note that the cognitive control effect around 350 ms after stimulus onset is named *N4 effect* by some authors and *P3 effect* by others. A *reduced P3* in the incongruent or Nogo condition hence equals what it is described as a *more negative* amplitude producing an *N4 effect* (for a review, see Zurrón, Pouso, Lindín, Galdo, & Díaz, 2009).

between pupil size and N4 amplitude, pointed towards improved cognitive flexibility (mental shifting) in bilingual compared to monolingual toddlers (Kuipers & Thierry, 2013). In an MEG study using a Simon task, Bialystok et al. (2005) found differences in brain activation correlated with reaction times between bilinguals and monolinguals. In bilinguals, faster reaction times were related to increased activity in superior and middle temporal, cingulate, and superior and inferior frontal regions, largely in the left hemisphere. In contrast, in monolinguals, faster RTs were correlated with increased activation in middle frontal areas (Bialystok et al., 2005). Moreover, concerning the performance of bilinguals on task switching, a bilingual advantage is not consistently found (for a review, see Hernández et al., 2013) and there is ERP evidence for partially independent neurocognitive processes underlying linguistic and non-linguistic switching (Magezi et al., 2012). Taken together, these studies suggest that even if bilingualism does not necessarily lead to a behavioral bilingual advantage in executive functions, regular multiple language use leads to changes in neural processing of executive control, e.g. conflict monitoring, inhibitory control or cognitive flexibility (mental shifting). Given the limitations of behavioral measures in studying control processes in bilingualism, the use of electroencephalography is a promising tool for investigating with high temporal resolution the time course of the different executive control processes involved in realizing tasks that necessitate the resolution of conflicts.

1.3.3.3. NEUROIMAGING FINDINGS ON THE IMPACT OF BILINGUALISM ON EXECUTIVE CONTROL

Abutalebi and Green (2008; see also, Green & Abutalebi, 2013) have proposed a neurocognitive model of bilingual language control. The following sites – involved in cognitive control processes - have been shown to be active in the control over bilingual language control: anterior cingulate cortex (ACC), prefrontal cortex (PFC), the basal ganglia (especially the caudate nucleus), the bilateral supramarginal gyri (SMG) and the parietal lobe only in case of high attentional load. These areas have equally been confirmed by a meta-analysis on functional neuroimaging studies on language switching (Luk et al., 2012; for a review, see also Hervais-Adelman, Moser-Mercer, & Golestani, 2011). Moreover, many of these regions are also involved in non-linguistic control (MacDonald et al., 2000; Shenhav et al., 2013; van Veen & Carter, 2006). Further evidence for an overlap of neurocognitive control processes in switching between languages and non-verbal task sets comes from a recent fMRI study investigating bilinguals' interference inhibition and switching performance in a verbal and a non-verbal task. Weissberger et al. (2015) found neuronal activation of similar distribution and strength for switching performance in verbal and non-verbal tasks but a more widespread activation for interference inhibition in the non-verbal as compared to the verbal task, which may indicate partially separate control mechanisms for verbal and non-verbal interference inhibition. Concerning the language background, further evidence suggests that the activation of the neural correlates of language control may vary as a function of proficiency (Abutalebi, Della Rosa, et al., 2013; Marian, Blumenfeld, Mizrahi, Kania, & Cordes, 2013), age of acquisition (AoA) of the L2 (Isel, Baumgaertner, Thrän, Meisel, & Büchel, 2010; Luk, De Sa, & Bialystok, 2011; Saur et al., 2009) or the dominant interactional context, i.e. single language or mixed language context (Wu & Thierry, 2013; see also Section 1.5). A higher activity in the dorsolateral prefrontal cortex (DLPFC) was observed in late bilingual individuals (French-German; AoA > 10; mean age 30,3 years) than in early bilinguals (French-German; AoA < 3; mean age 32,5 years; Isel et al., 2010). Isel and colleagues (2010) proposed that the higher involvement of the prefrontal cortex in late bilinguals might reflect a higher cost in language switching. Moreover, in multilinguals also the left caudate nucleus appears to be essential in monitoring and control of language alternatives (Crinion et al., 2006). A few studies taking a more holistic testing approach administered a whole battery of executive function tests in order to study domain-general control processes involved in the language domain. Their findings corroborate the hypothesis that there are shared cognitive and neuronal resources for domain-general and linguistic control processes (Carlson & Meltzoff, 2008; for a study not specifically on bilingualism but on linguistic processes in general, see Fedorenko, Duncan, & Kanwisher, 2013). Badzakova-Trajkov (2008) examined neuronal activity in two groups of late, proficient bilinguals (Macedonian-English; mean age 26,4 years; German-English; mean age 25,9 years) and in monolinguals (English, mean age 27,5 years) in a Stroop task. Comparing the main areas of activation in Stroop interference (i.e. processing the conflicting information between a written color word and its different ink color) between language groups, monolinguals showed greater activation in the prefrontal cortex and in the ACC in comparison to bilinguals, which may indicate a greater cost in conflict resolution in monolinguals. In this study, late proficient bilinguals showed similar neuronal activity in both languages (Badzakova-Trajkov, 2008). In an fMRI study, Abutalebi et al. (2012) using a flanker task found a reduced activation in the dorsal part of the ACC in bilinguals, thought to reflect more efficient cognitive conflict processing at the neural level in bilinguals. Moreover, this cortical effect was mirrored by a behavioral bilingual advantage. Furthermore, Luk, Bialystok, Craik and Grady (2011) have shown that with aging white matter integrity is better maintained in bilinguals compared to monolinguals. White matter connectivity is required for information transfer between neurons and a decline in white matter integrity is frequently observed with aging and associated with cognitive decline (Madden et al., 2009). Furthermore, a study testing Spanish monolinguals and Spanish-Catalan bilinguals in a non-verbal color shape switching task found a reduced switching cost in bilinguals (Garbin et al., 2010). The fMRI data revealed increased activation in the right inferior frontal gyrus (IFG) and the ACC for monolinguals while bilinguals showed increased activation in the left IFG and the left striatum, areas involved in language control. These data support the idea that neural networks are partially shared between linguistic and non-linguistic cognitive control (Garbin et al., 2010).

To sum up, the neural network involved in domain-general cognitive control (MacDonald et al., 2000; Shenhav et al., 2013; van Veen & Carter, 2006) appears to largely overlap with the neural network involved in bilingual language control (Abutalebi, Della Rosa, et al., 2013; Buchweitz & Prat, 2013; de Bruin et al., 2014; Green & Abutalebi, 2013; Kroll & Bialystok, 2013; Luk et al., 2012). This may explain the bilingual advantage in cognitive control also in non-linguistic domains (Bialystok et al., 2012; Kroll & Bialystok, 2013). However, some studies have also shown evidence in favor of a partially qualitative difference between domain-general and bilingual language control (Calabria et al., 2012; Magezi et al., 2012; Weissberger et al., 2015). Among the studies that examined the differences of neural correlates between bilinguals and monolinguals in cognitive control processes, it emerges that the same network but slightly different activation patterns are involved for bilinguals (Bialystok et al., 2005), and/or that neuronal control processing is more efficient in bilinguals (Abutalebi et al., 2012; for a review, see Bialystok et al., 2012).

1.3.4. LESS CAN BE MORE? ON THE OPTIMAL LEVEL OF COGNITIVE CONTROL.

Having presented the nature of the advantages of more efficient cognitive control in performing linguistic and non-linguistic tasks, it is now important to state that increased cognitive control involvement may be beneficial for many neurocognitive processes but that there are also benefits of reduced top-down control involvement at specific stages of development or for certain cognitive functions. In the *matched filter hypothesis* (MFH) of cognitive control, Chrysikou, Weber and Thompson-Schill (2013) claim that the optimization of task performance does not simply follow a ‘the more the better’ – logic of top-down involvement but that a good match between cognitive control involvement and the necessity to filter bottom-up information in a given task produces optimal performance. The degree of matching between organism- and task-specific constraints may vary as a function of developmental stage, genotype, long-or short-term disruption of brain function, etc. To give an example, it may be inadequate to consider hypofrontality in children, i.e. lower degree of top-down cognitive control involvement, as a deficiency. The heterochronous development of different parts of the human brain, with for instance the prefrontal cortex reaching maturation relatively late in development (A. Diamond, 2002; Leisman, Machado, Melillo, & Mualem, 2012), enables for an efficient acquisition and mastery of certain cognitive faculties. For example, language acquisition in children is driven in a bottom-up manner, linguistic input is soaked up to a large part without guided instruction to focus on particular language phenomena, which allows the extraction of the linguistic patterns (i.e. extraction of grammatical regularities; Chrysikou et al., 2013). One general principle may be that in general, “during periods in which evolutionary pressures have placed a premium on learning over task execution, it may be beneficial for the organism to limit the filtering of information by reducing PFC activity” (Chrysikou et al., 2013, p. 2). On the other hand, as mentioned above, in adult L2 or L3 language learning, explicit knowledge in focused L2 instruction and top-down control may be beneficial in order to facilitate and accelerate L2 grammar acquisition (Paradis, 2009). The acquisition processes itself may function in a similar way as it does in children, but probably less efficiently (Paradis, 2009, p. 106s). Moreover, hypofrontality might not only be beneficial for the acquisition of language and other cognitive and motor faculties in children but short phases of reduced top-down control may be beneficial in certain cognitive functions, such as creativity (Chrysikou et al., 2013).

1.4. NEUROPLASTICITY IN BILINGUALISM

1.4.1. NEURAL PLASTICITY OVER THE LIFESPAN

Neural plasticity or neuroplasticity refers to changes in the neural pathways and synapses that underlie changes in behavior, thinking, and emotions. The concept of neural plasticity is in opposition with the formerly-held position that the brain is a physiologically static organ. There is increasing evidence for persisting neural plasticity from childhood (A. Diamond, 2011, 2013; A. Diamond & Lee, 2011) during adulthood until old age (Burke & Barnes, 2006; Dahlin, Nyberg, Bäckman, & Neely, 2008; Erickson et al., 2007; for reviews, see Draganski & May, 2008; Greenwood & Parasuraman, 2010; S.-C. Li, 2013;

Lourenco & Casey, 2013; Lövdén, Wenger, Mårtensson, Lindenberger, & Bäckman, 2013; May, 2011). Sustained cognitive and motor activity and training can induce neural plasticity during adulthood (Draganski & May, 2008; Erickson et al., 2007). Critical periods in development have been shown to be related to GABA-levels in the brain, with an important role that GABA is playing in neural maturation. Once a certain degree of maturation achieved, the effect GABA is having on neurons will become inhibitory and the critical phase closes. Serotonin and GABA have been shown to be neurotransmitters that play a major role in regulating plasticity (Baroncelli et al., 2011). Hence, reducing the inhibition levels (e.g. genetical or pharmacological reduction of GABA levels in animal studies) has been shown to have a potential to induce neuronal plasticity even in adulthood (for a review on the specificities of mammalian adult neural plasticity using the example of the visual cortex, see Karmarkar & Dan, 2006; moreover, benzodiazepine injection has been shown to prevent plasticity induction; Sale et al., 2007). Beyond genetical or pharmacological manipulation, environmental enrichment (Baroncelli et al., 2010) or deprivation (e.g. plasticity induction by maintained confrontation to complete darkness; He, 2006; Huang, Gu, Quinlan, & Kirkwood, 2010) have been shown to induce neural plasticity. Based on these observations on genetic, molecular and environmental influences on neuroplasticity, two hypotheses on the neuroplasticity-inducing mechanisms have been formulated: (1) a reduction of GABAergic inhibition levels may reinstate neural plasticity or (2) overall increase of cortical activity due to changes in the excitement-inhibition balance is the key to plasticity reinstation (Baroncelli et al., 2011; Morishita & Hensch, 2008). Activity-dependent modulations of gene transcription may be critically involved in promoting plasticity (Baroncelli et al., 2011). Structural changes following induced plasticity by environmental enrichment have the potential to be long-lasting (Sale et al., 2007). However, opening a window of neural plasticity leads to network change, which can lead to improvement but also the destruction of established connections, which indicates that induced plasticity also renders the network more vulnerable (Arnsten, Wang, & Paspalas, 2012; Baroncelli et al., 2011). To come back to language, it is clear that language learning constitutes a form of environmental enrichment, and beyond the communicative and cultural enrichments that comes along with the acquisition of another foreign language, the integration of the second language in a language system with a consolidated first language comprises certain risk factors, i.e. entrenchment, parasitism, misconnection, and negative transfers. Hence, during L2 learning an interplay between risk-generating processes and protective, support processes, i.e. resonance, internalization, chunking, positive transfer, and participation, plays an important role (MacWhinney, 2008, 2012). There is evidence that neural plasticity is actively limited at the cellular and molecular level and that both, structural as well as functional "brakes" of neuronal plasticity exist (Bavelier, Levi, Li, Dan, & Hensch, 2010). Thus, reducing the impact of plasticity "brakes" has been found to experimentally as well as naturally induce increased neuronal plasticity in adult organisms. Amongst the structural plasticity "brakes", perineuronal nets or myelin seem to play a role in inhibiting neurite outgrowth. Functional plasticity "brakes" may act directly upon the excitatory-inhibitory balance within local circuits (Bavelier et al., 2010). The functional relevance of these brakes may help guaranty, in a mature state of the organisms, the availability of a behavioral repertoire allowing the rapid and accurate reaction in habitual situations that are re-occurring to a high degree of probability in a similar manner. This behavioral repertoire and the control over it are in large parts acquired through the repeated confrontation with environmental constraints the organisms has to deal with and adapt to during development. However, in case of changes occurring in the environment or of voluntary immersion into new situations, an adaptive capacity is required, a definitive closure of neural plasticity would be harmful. Genetic, pharmacological and environmental removal of brakes has been studied in animals (Bavelier et al., 2010). The underlying mechanisms are less known in humans, but studies on recovery in pathological populations (Baroncelli et al., 2011; Bavelier et al., 2010; Sale, Berardi, & Maffei, 2009) as well as cognitive plasticity in healthy populations give insight on the factors acting upon neuronal plasticity and changes in humans. Activity-dependent long-term neuroplastic structural changes will be addressed in the following section.

1.4.2. ACTIVITY/TRAINING-INDUCED MODULATIONS IN NEURONAL ARCHITECTURE

Through neuroplastic changes, the neuronal architecture overall or of specific neurocognitive networks can be modulated by environmental factors, substance administration or mental and physical activity (Arnsten et al., 2012; Bryck & Fisher, 2012). These factors vary concerning the time scales and permanence of the induced modulation. Thus, considering short-term modulations, PFC function can be enhanced by moderate states of arousal, such as those induced by intentional states (Filevich, Kühn, & Haggard, 2012; Leisman et al., 2012) and motivation (Kouneiher, Charron, & Koechlin, 2009; Padmala & Pessoa, 2010; Shohamy, 2011; Somerville & Casey, 2010; Wise, 2004), or by administration of moderate doses of psychostimulant substances (Berridge & Arnsten, 2013), while keeping widely unchanged the existing neuronal architecture. However, short-term depleted PFC functioning can be found as an effect of fatigue, stress or high doses of psychostimulants, which induce either too low (fatigue) or too high levels (stress, psychostimulant overdoses) of dopamine (DA) and norepinephrine (NE) resulting in a less well-structured firing pattern of PFC neurons (Arnsten, 2009; Arnsten, Paspalas, Gamo, Yang, & Wang, 2010; Arnsten et al., 2012; Berridge & Arnsten, 2013). While short-term exposure to the above-mentioned factors can lead to modulations of the PFC function with the neuronal connective structure remaining widely unchanged, long-term exposure can induce architectural modulations. PFC connective patterns can be modulated via modifications of the density and localization of ion channels, synapses or the neuronal cell structure, or the recruitment of fewer or additional neurons and neuronal regions (Arnsten et al., 2010). Long-term structural changes in the ACC and/or PFC and their increased functional efficiency have been observed as a consequence of regular practice of specific activities, such as multiple language use (Abutalebi et al., 2012; Baum & Titone, 2014; Bialystok et al., 2012; Kroll & Bialystok, 2013; Luk, Bialystok, et al., 2011), making music (Fauvel et al., 2014; Hanna-Pladdy & MacKay, 2011; Moreno et al., 2011), strategy board game play (Jung et al., 2013), doing sports (Bezzola, Merillat, Gaser, & Jancke, 2011), playing video and computer games (Basak, Boot, Voss, & Kramer, 2008; Bavelier et al., 2011; Bialystok, 2006; Boot, Kramer, Simons, Fabiani, & Gratton, 2008), or in behavioral skill training involving neurofeedback (Enriquez-Geppert, Huster, & Herrmann, 2013; for reviews, see A. Diamond, 2011, 2013; A. Diamond & Lee, 2011), while depletions of the PFC are often the case in psychiatric disorders (Arnsten & Rubia, 2012; Millan et al., 2012) or can occur due to sustained exposure to stress (Arnsten, 2009; Cook & Wellman, 2004; Gray, Milner, & McEwen, 2013; Liston, 2006; Radley et al., 2008), substance abuse (Berridge & Arnsten, 2013) or follow from certain activities, such as media multitasking (i.e. the degree of concurrent use of multiple media, e.g. print media, television, computer-based video, music, telephone and mobile phone voice calls, text messaging, email, etc.; Ophir, Nass, & Wagner, 2009). Regarding more closely the case of multiple language use, classroom learning might constitute a form of environmental enrichment. However, immersion in a non-native language environment is frequently an even stronger constraint requiring adaptation, leading in the long run to better outcomes in linguistic and metalinguistic skills in the native language as well as the language of immersion (Hermanto, Moreno, & Bialystok, 2012). Recent findings of a cognitive control advantage with second language immersion corroborates this idea (Bialystok & Barac, 2012; Nicolay & Poncelet, 2013).

1.4.3. FUNCTIONAL CONNECTIVITY CHANGES WITH BILINGUAL EXPERIENCE

Some studies have examined functional connectivity changes with bilingual experience and the results are somewhat heterogeneous. Functional connectivity analyses investigate the statistical dependencies among remote neurophysiological events, inferred from correlations between measurements of neuronal activity (Friston, 2011). Dodel et al. (2005) investigated the relation of L2 proficiency with the functional connectivity during syntactic processing and found the functional connection between regions that have previously been related to syntactic processing and language production, such as the left inferior frontal gyrus, putamen, insula, precentral gyrus and the supplementary motor area, to be enhanced during sentence production in the L2 compared to L1, in (syntactically) more proficient bilinguals compared to less proficient ones. Similarly, for lexical learning of their L2 Chinese, good learners were found to have increased functional connectivity in phonological processing areas as compared to poor learners (Veroude, Norris, Shumskaya, Gullberg, & Indefrey, 2010). This study also demonstrated that pre-existing as well as learning-induced functional connectivity characteristics distinguished good from poor L2 learners (Veroude et al., 2010). However, a study investigating functional connectivity changes during initial L2 lexical learning found that the increase in L2 proficiency was associated with a decrease in functional integration between the language and control systems (Ghazi Saidi et al., 2013). However, it is to be noted that this observation which was made on initial L2 learners may not be valid for advanced L2 learners, who would plausibly show different functional connectivity patterns (Ghazi Saidi et al., 2013). Moreover, in a short-term memory task, Majerus et al. (2008) found higher functional connectivity between the left intraparietal sulcus and bilateral superior temporal and temporo-parietal areas, in low proficient bilinguals compared to highly proficient bilinguals. This was interpreted to reflect less specific and differentiated activation of the short-term memory network in low proficient bilinguals. Abutalebi and Green (2007) as well as Ghazi Saidi et al. (2013) suggested that higher proficiency would result in less effortful, and thus more automatic, processing, reflected in decreased functional integration between the language and control networks.

1.4.4. STRUCTURAL CHANGES OF GRAY MATTER (GM) AND WHITE MATTER (WM) WITH BILINGUAL EXPERIENCE

Structural neuronal reorganization coming along with a long-term activity such as multiple language use, has been investigated on gray matter (GM) and white matter (WM) characteristics. Increases in gray matter density may reflect increases in the myelination of cortico-cortical connections and/or synaptic pruning and increases in white matter density or volume may be due to increases in the diameter and myelination of the axons forming the fiber tracts as well as to increases in neuronal size and glia proliferation (for a brief overview, see Giorgio et al., 2010). GM density has been found to be increased in the left putamen in multilinguals compared to monolinguals (Abutalebi, Rosa, et al., 2013) and in the left inferior parietal cortex in bilinguals compared to monolinguals (Mechelli et al., 2004). Moreover, with GM density in the left inferior parietal cortex being overall higher in bilinguals compared to monolinguals, modulations were also found within the bilingual group: GM density was observed to be positively correlated to L2 proficiency and negatively correlated to age of L2 acquisition (Mechelli et al., 2004). Moreover, Stein et al. (2012) show that after a five-months L2 learning period, the increase in second language proficiency (however not absolute proficiency) was correlated with an increase in gray matter density in the left inferior frontal gyrus (IFG). Similar to Mechelli et al. (2004), Mårtensson et al. (2012) found increased cortical thickness in the left inferior frontal gyrus (IFG) related to intense language training, but changes in cortical thickness were not limited to this region and was also observed in the left middle frontal gyrus (MFG) and the left superior temporal gyrus (STG) in the group confronted to intense language learning. Moreover, proficiency in the studied language was found to be positively correlated to cortical thickness in the right hippocampus and the left STG while learning effort was positively correlated with cortical thickness in more frontal regions, in the left MFG (Mårtensson et al., 2012). Finally, Klein, Mok, Chen and Watkins (2013) investigated the impact of age of second language acquisition and observed increased GM density in the left IFG in sequential bilinguals compared to monolinguals, but no difference between simultaneous bilinguals and monolinguals. Moreover, age of L2 acquisition was positively correlated to cortical thickness in the left IFG and superior parietal cortex but negatively related to cortical thickness in the right IFG.

To sum up, bilingualism appears to be related to increases in gray matter density most robustly in left inferior parietal and left inferior frontal regions. Moreover, individual differences in second language proficiency are positively related to cortical thickness in the left inferior parietal, left inferior frontal, left superior temporal cortices and the right hippocampus while age of acquisition is negatively related to cortical thickness in the left inferior parietal cortex and right inferior frontal cortex but positively related to cortical thickness in the left inferior frontal gyrus and the superior parietal lobe.

Only few recent studies also addressed the question of the changes in the neuronal substrate in bilingualism by investigating the white matter connectivity characteristics. A frequently used measure of white matter connectivity via diffusion tensor imaging (DTI)-based anatomical connectivity analyses is fractional anisotropy (FA). FA values are thought to reflect variations in the number of axons, axon density, size of axons and degree of myelination and have been found to correlate with information transition properties, such as information processing speed (Mohades et al., 2012). A study comparing neuronal connectivity in early bilingual adults and monolinguals (García-Pentón, Pérez Fernández, Iturria-Medina, Gillon-Dowens, & Carreiras, 2014) found two highly interconnected regions (i.e. sub-networks) to be significantly stronger connected in bilinguals than in monolinguals. The first sub-network involved six highly interconnected nodes – all of which have been found to play a role in language processing and in bilingualism: the insula (INS), the superior temporal gyrus (STG), pars triangularis (PT) of the inferior frontal gyrus (IFG), the supramarginal gyrus (SMG), the pars opercularis (PO) of the inferior frontal gyrus and the medial superior frontal gyrus (MSF). The second sub-network involved five nodes – which have previously been found to be implied in language processing or in functions related to language: the left superior occipital gyrus (SOG), right superior frontal gyrus (SFG), left superior parietal gyrus (SPG), left superior temporal pole (STP) and left angular gyrus (ANG). In this second sub-network, apart from the STP and ANG reported to be involved in language processing, SOG is supposed to be implied in high level visual processing of letters and words, SFG in language control and the SPG in visuo-spatial processing during visual word processing (García-Pentón et al., 2014). However, the over-development of the connection efficiency in the sub-networks relevant in bilingualism was accompanied by a reduction in global network efficiency, as it is frequently seen in systems with limited resources (García-Pentón et al., 2014). In a study investigating white matter plasticity change in second language learning, Schlegel, Rudelson and Peter (2012) found that an intermediate period (9 months) of intense language learning in young adults was accompanied by FA increases between left hemispheric language areas and in right temporal areas as well as in the frontal axonal tracts that cross the genu of the corpus callosum. Moreover, the longitudinal assessment of FA changes revealed a positive correlation between individual participant slopes of FA changes and the degree of language learning, as evaluated by the language instructor. One further finding in this study was, that the caudate nucleus was highly connected by those fiber tracts showing changes in bilingualism. This finding supports the idea of the role of the caudate in language learning (Schlegel et al., 2012). Moreover, in intensive language learning L2 proficiency-related laterality shifts in structural connectivity in the perisylvian language network have been observed (Xiang et al., 2015). In less proficient L2 speakers, structural connectivity in the BA6-temporal pathway (mainly along the arcuate fasciculus) showed a right hemispheric dominance while with increasing proficiency, a stronger left hemispheric dominance emerged. It is suggested that the stronger right hemispheric dominance in less proficient L2-learners may reflect the recruitment of additional right-hemisphere areas during phonological processing (Xiang et al., 2015).

Exploring white matter (WM) connectivity in bilingual children, Mohades et al. (2012) found increased FA values in the left inferior occipito-frontal fasciculus (LIFOF) in simultaneous bilinguals compared to sequential bilinguals and monolinguals. In contrast, FA values for the fibers arising from the anterior part of the corpus callosum (AC) projecting to the orbital lobe (AC-OL) revealed lower FA values in simultaneous bilinguals compared to monolinguals. Hence, the higher FA values in LIFOF found simultaneous bilinguals support the idea that semantic processing and transmission of semantic information is fastest in simultaneous bilinguals compared to sequential bilinguals and monolinguals (Mohades et al., 2012). However, the reduced FA values in AC-OL fibers in simultaneous bilinguals is interpreted to be possibly due to a more bilateral cerebral distribution of language areas in simultaneous bilinguals and as a consequence differences in CC size compared to sequential bilinguals and monolinguals – both likely presenting a more left-lateralized dominance of language patterns. Further studies would be required to obtain a more precise idea of differences in AC-OL related to bilingualism (Mohades et al., 2012). Last, in a study on the bilingual impact on the maintenance of white matter connectivity in aging, Luk et al. (2011) found higher FA values in the corpus callosum and extending posteriorly to the bilateral superior longitudinal fascicule, and anteriorly to the right inferior frontal-occipital fasciculus and uncinate fasciculus. Moreover, an overlay of stronger anterior posterior functional connectivity and the mentioned stronger WM connectivity (higher FA values) especially in longitudinal fasciculi was found for bilinguals. These connectivity changes are interpreted to probably be involved in the bilingual advantage frequently found in executive function performance (Luk, Bialystok, et al., 2011). To sum up, bilingual life experience seems to be reflected by enhancements of white matter connectivity especially between typical language areas and in longitudinal fiber tracts as well as between language and control areas, i.e. areas in the frontal lobe and the caudate nucleus. However, findings on connectivity changes in the corpus callosum (CC) remain less unanimous, with both, increases and decreases of WM connectivity found in bilinguals. Yet, age of bilingualism onset might be the crucial factor to explain the direction of WM changes in the CC, and simultaneous bilingualism might be associated with reductions and sequential bilingualism with increases of WM connectivity in the CC. The reason underlying could be the more bilateral distribution of language areas in simultaneous bilinguals compared to a stronger left-lateralized dominance of language areas in sequential bilinguals.

1.4.5. RELATION BETWEEN FUNCTIONAL AND STRUCTURAL CONNECTIVITY

Structural strengthening of connections within specific sub-networks due to bilingual experience might be accompanied by loosening of connectivity strength in the global cerebral network, a phenomenon frequently found in systems presenting limited resources. Moreover, there are hints, that functional connectivity measures between cerebral regions are related to structural white matter connectivity (FA measures; Luk, Bialystok, et al., 2011). However, the BOLD signal correlates with changes in neural activity in gray matter but is relatively insensitive to neural activity in white matter (Schlegel et al., 2012). Moreover, a question that also requires further research is the relationship between gray matter and white matter changes during learning, still requiring better understanding (Taubert et al., 2010). Finally, the literature review given in the preceding sections on neuroplasticity underline, that even if neuronal plasticity is maximal during childhood and adolescence, the human brain retains a high level of plasticity and capacity to reorganize in learning during adulthood and activity-dependent ‘connectivity-training’ may contribute to delays in neuronal and cognitive decline with aging.

1.5. LANGUAGE BACKGROUND PARAMETERS IN BILINGUAL LANGUAGE PROCESSING AND CONTROL

In an extensive review on the question of how bilingualism relates to executive functions, Valian (2015) stresses the point that individuals, and especially bilinguals with their diverse ways of using their languages, differ from each other in the complexity of activities that can improve their executive functions. The diversity of the language background should be kept in mind when looking at the heterogeneity of findings in the domain of research relating language and executive control. As it has been claimed by Grosjean (1998), a problem in the psycholinguistic literature on bilingualism is that the types of bilinguals tested in the different studies differ on a range of variables, which are, moreover, in some cases not being assessed. Consequently this poses certain limits on the comparison across studies. According to Grosjean (1998), factors that play a role in characterizing types of bilingualism are found within the bilingual language history and the language relationship (time and manner of respective language acquisition, the cultural context and pattern of language use), language stability (a language still being acquired or restructured due to a change of the linguistic environment), language proficiency, language mode (monolingual, bilingual – with varying patterns of code switching or mixing or borrowings) or biographical variables (age, sex, socioeconomic and educational status; Grosjean, 1998). However, there are very successful approaches of systematically studying the neuronal and cognitive impact of these variables and an outline for the following factors will be given below: *age of second language acquisition*, *second language proficiency*, *second language immersion experience* and the *interactional context and frequency of language switching*. These language background factors are amongst the best studied ones in the bilingualism literature. Findings issued from this research corroborate even more that it is essential to assess the background information in order to render comparisons across studies meaningful.

Moreover, beyond the already mentioned ones, the following factors may also have an impact on control involvement in bilingualism and hence shall get further consideration in the bilingual language background assessment, e.g. the frequency of L1 and L2 use (Flege, Yeni-Komshian, & Liu, 1999; Tu et al., 2015), the language typology and the typological distance between languages (van Heuven, Conklin, Coderre, Guo, & Dijkstra, 2011), motivation, affective components and language valorization (Csizér & Dörnyei, 2005; Dörnyei, 2003; Gardner, 2007; Somerville & Casey, 2010), as well as the number of languages used beyond the L1 and L2 (multi- or plurilingualism; Marian et al., 2013; Poarch & van Hell, 2012) and their proficiency and frequency of use. Concerning the typological distance between L1 and L2, we are aware that it is extremely complex in linguistics to define an absolute distance for typology between languages. However, in some domains of linguistics, such as phonology, it is possible to determine whether sounds exist or do not exist in two languages or whether they are identical or similar (Flege, 1995). One can hypothesize that the degree of control required to limit negative transfers of grammatical knowledge from L1 to L2 for early learners (and from L2 to L1 for highly proficient bilinguals) may be related to the typological distance between the languages. One hypothesis could be that when a phenomenon is similar (but not identical) in L1 and L2, it is more difficult to master. Finally, there is an important degree of individual differences beyond language background factors, which also play a role in second language learning and acquisition and consequently also for the interplay between language and executive functions, cf. section 1.5.5.

1.5.1. AGE OF SECOND LANGUAGE ACQUISITION

The origin of age of acquisition (AoA) effects in second language acquisition have been explained by different theoretical accounts, some of which claim the existence of a critical (or sensitive or optimal) period in early childhood during which optimal language acquisition can take place while after the closure of the supposed critical period language acquisition is claimed to be possible only to a limited degree (Lenneberg, 1967; for a review, see DeKeyser & Larson-Hall, 2005). Other theoretical accounts, however, postulate that effects of age of acquisition are not produced by the existence of a critical period but by developmental changes in the interplay between plasticity and stability of neuronal tissue; e.g. the later an L2 is acquired, the more difficult becomes its integration into an increasingly consolidated L1 and its neuronal substrate (A. E. Hernandez & Li, 2007; A. Hernandez et al., 2005; P. Li et al., 2007; MacWhinney, 2012). The mechanisms of the interplay of neuronal plasticity and stability are supposed not to be specific to the language domain but the neuronal and computational mechanisms underlying sensorimotor and memory maturation are thought to be determining in all, linguistic as well as non-linguistic, domains (DeKeyser & Larson-Hall, 2005; A. E. Hernandez & Li, 2007). The idea that developmental changes in sensorimotor processing and memory are crucial in accounting for AoA effects also explains the finding that syntax, especially morphosyntax, is more sensitive to AoA than semantics (A. E. Hernandez & Li, 2007). Different evidence also points towards an AoA sensitivity of especially phonetics, i.e. an increasing foreign accent with increasing AoA, but less so of a decrease in morphosyntactic performance, which, on the other hand, is also largely determined by years of education (Flege et al., 1999). For a more detailed elaboration of these theoretical positions, see also section 1.2.1.

Weikum et al. (2013) studied the impact of the age of acquisition of the L2 on the capacity to visually discriminate the L2 from other languages. Participants watched silent movies of speakers' faces and had to identify if their L2 or another language which they did not master themselves was spoken. Adult participants who had been confronted to their L2, English, during infancy (0-2 years) or early childhood (2-6 years) managed do visually discriminate the L2 from other languages when watching silent movies of speakers' faces. However, participants who had acquired the L2 only from their late childhood (6-15 years) on failed to do so, despite of high L2 proficiency in all AoA groups. These findings suggest that the confrontation to a given language before the age of 6 years renders possible the capacity to visually discriminate this language in adulthood and it was suggested that the acquisition of some visual language cues is dependent on sensitive periods (Weikum et al., 2013). However, there is also evidence against the idea of a sensitive period, supporting the view that L2 acquisition proceeds equivalently, with respect to the neuronal resources involved, independent if the L2 is acquired early or late in life (Abutalebi, 2008). Moreover, it has been claimed that even if there may be no qualitative differences, the L2 acquisition at an older age probably proceeds in a less efficient way than in early childhood (Paradis, 2009, p. 106s). Furthermore, late L2 appropriation of implicit knowledge of a language (language acquisition) may benefit from focused language instruction involving the appropriation of explicit knowledge of the L2 (language learning; Paradis, 2009). It has been shown that the degree of explicit and implicit knowledge transmission in second language instruction leads to different outcomes on the level of the neuronal activation in late second language appropriation (Morgan-Short, Steinhauer, Sanz, & Ullman, 2012).

Age of second language acquisition has been found to be positively related with cortical thickness in the left inferior frontal gyrus (IFG) while it was negatively correlated with cortical thickness in the right IFG (Klein et al., 2013). These differences in cortical thickness also distinguished late sequential bilinguals from simultaneous bilinguals as well as monolinguals, while simultaneous bilinguals did not differ from monolinguals (Klein et al., 2013). This finding might indicate that in later sequential L2 acquisition, suboptimal neuronal circuits are recruited for language learning (Klein et al., 2013). Moreover, there is evidence, that late bilinguals recruit additional control resources in order to handle multiple language use (Isel et al., 2010; Luk, De Sa, et al., 2011). A higher activity in the dorso-lateral prefrontal cortex (DLPFC) was observed in adult late bilinguals (French-German; AoA > 10) than in early bilinguals (French-German; AoA < 3), which was thought to reflect a higher cost in language switching (Isel et al., 2010). Luk et al. (2011) demonstrated in a behavioral study that early bilinguals (L2 AoA < 10) perform better in an interference control task, i.e. the flanker task, than late sequential bilinguals (L2 AoA > 10), which is thought to reflect more efficient control coming along with longer bilingualism experience. In contrast, in an attentional network task (ANT), Tao et al. (2011) observed that late bilinguals showed a greater bilingual advantage in conflict resolution compared to early bilinguals (with both groups performing better than monolingual controls). On the other hand, early bilinguals showed better conflict monitoring performance than late bilinguals (with again both groups performing better than monolingual controls; Tao et al., 2011). Finally, simultaneous bilinguals have also been observed to produce fewer unintentional language switches than non-simultaneous bilinguals, which indicates that especially early bilingualism improves cognitive control (inhibition; Rodriguez-Fornells, Krämer, Lorenzo-Seva, Festman, & Münte, 2012). To sum up, most findings point towards increased cognitive control in simultaneous bilingualism compared to sequential bilingualism, especially in conflict monitoring, while the evidence is more mitigated for inhibition.

1.5.2. SECOND LANGUAGE PROFICIENCY

In a review on the influence of language background parameters on the neural bases of the bilingual language system, Abutalebi et al. (2005) conclude that the age of second language acquisition is relevant but that L2 proficiency may be the most determining factor. Increasing L2 proficiency is usually reflected by an increasing overlap of neural activation patterns in the L1 and the L2 (for a review, see Abutalebi & Green, 2007), while more extensive activation patterns with low L2 proficiency are thought to reflect the recruitment of additional resources, e.g. for language control (for a review, see Abutalebi, 2008). Based on the *Revised Hierarchical Model* (Kroll & Stewart, 1994; Kroll et al., 2010; see also section 1.2.1), high control demands should be expected especially in low proficient bilinguals because L2 processing requires the activation of L1 translation equivalents, which subsequently need to be suppressed. With increasing proficiency, however, direct links between L2 lemmas and concepts become stronger while the links to the L1 translation equivalents get weaker, which leads to smaller inhibitory control demands. Similarly, Abutalebi and Green (2007) argue that the manner in which the neurocognitive network of bilingual language control operates depends on the individual's L2 proficiency. The basic assumption is that with increasing L2 proficiency there is a shift from controlled to automatic processing, which is reflected by a reduction in prefrontal activity. A less automatic language, such as an L2 not mastered with high proficiency, requires controlled processing (Bialystok & Feng, 2009; Francis, Tokowicz, & Kroll, 2014) and hence engages, amongst others, more extended portions of the left prefrontal cortex (Abutalebi & Green, 2007), the left caudate and anterior cingulate cortex (Abutalebi et al., 2008), while this is not the case for the more automatic language, usually the L1 (Segalowitz & Hulstijn, 2005). Further evidence shows that control over a language mastered at lower proficiency is associated with higher activation in the caudate (Abutalebi, Della Rosa, et al., 2013) or the left putamen (Abutalebi, Rosa, et al., 2013), both structures of the basal ganglia which have been shown to be involved in language control (Ali, Green, Kherif, Devlin, &

Price, 2010; Argyropoulos, Tremblay, & Small, 2013; Crinion et al., 2006) as well as non-linguistic control (Ford & Everling, 2009; Groenewegen, 2003).

Costa and collaborators suggested that a different control mechanism is used by highly as compared to low proficient bilinguals (Costa & Santesteban, 2004; Costa et al., 2006; see also, section 1.3.2.4). Accordingly, in highly proficient bilinguals, lexical selection is thought to operate via a language-specific selection mechanism while in low proficient bilinguals, lexical selection requires the involvement of inhibitory control (Costa, 2005). Empirical evidence also suggests, that in highly proficient bilinguals, linguistic similarity between the two languages or L2 AoA does not affect lexical selection performance, whereas in low proficient bilinguals these two factors do play a role (Costa et al., 2006). Nonetheless, there is also evidence supporting the idea that even in highly proficient bilingualism, (inhibitory) control is involved in the control over the two languages (Abutalebi & Green, 2008; Guo, Liu, Misra, & Kroll, 2011; Y. Wang, Kuhl, Chen, & Dong, 2009).

Several cross-sectional studies have investigated the effect of L2 proficiency on the neuronal underpinnings of bilingual language representation and control. Wartenburger et al. (2003) found that neuronal activity patterns differed as a function of second language proficiency especially for semantic processing. That is, low proficient bilinguals showed more extensive cerebral activations during semantic judgment tasks than highly proficient bilinguals in Broca’s area and the right middle frontal gyrus while highly proficient bilinguals showed greater activation in the left middle frontal and right fusiform gyrus compared to low proficient bilinguals. Both groups, highly and low proficient bilinguals, showed greater activation during semantic processing in the L2 as compared to the L1 (Wartenburger et al., 2003). Higher L2 proficiency has been associated with better interference control on the level of sentence interpretation (Filippi, Leech, Thomas, Green, & Dick, 2012).

In diverse tasks involving control, it has been found that bilinguals with higher compared to those with lower L2 proficiency showed either an overall executive control advantage in a Stroop task

(Coderre, Van Heuven, & Conklin, 2012), an advantage in cognitive flexibility and self-regulation (S. H. Chen, Zhou, Uchikoshi, & Bunge, 2014), an advantage in conflict monitoring but less so in inhibitory control in an oculomotor control task (Singh & Mishra, 2013, 2015), as well as a global processing advantage (Mishra, Hilchey, Singh, & Klein, 2012; Singh & Mishra, 2012). In contrast, balanced L1 and L2 proficiency compared to unbalanced proficiency has been associated with a higher advantage in conflict resolution (rather than monitoring) in an attention network task (Poarch & van Hell, 2012; Tao et al., 2011) and a Simon task (Poarch & van Hell, 2012). Similarly, an increased advantage with L2 proficiency on inhibition has also been found in an attentional blink task (Khare, Verma, Kar, Srinivasan, & Brysbaert, 2013). Moreover, highly proficient bilinguals also appear to have more efficient disengagement of attention from task-irrelevant inputs, i.e. reflecting enhanced attention to task goals (Mishra et al., 2012). In a study on the effects of L1 and L2 proficiency on attentional control performance, Tse and Altarriba (2014) found that bilingual children's higher L2 proficiency (and the L2:L1 ratio indicating the degree of balanced proficiency) was associated with increased conflict resolution (inhibition) and working memory capacity (updating), but not goal maintenance (updating) or task-set switching (shifting), when they performed cognitive tasks that demanded attentional control. These findings suggest that not all of the components in Miyake et al.'s (2000) control framework (inhibition, updating, shifting) are equally sensitive to bilinguals' L1 and L2 proficiencies. In another cross-sectional study, Majerus et al. (2008) investigated short-term memory capacity as a function of L2 proficiency. In this fMRI study, the hemodynamic activity and the functional connectivity was compared between highly and low proficient bilinguals during a short-term memory task. High and low proficiency groups showed similar activation of encoding and retrieval short-term memory networks (fronto-parietal and fronto-temporal). However, the highly proficient bilinguals showed higher activation of the left orbito-frontal cortex during encoding and the bilateral superior frontal cortex during retrieval as compared to the low proficient group. On the other hand, the low proficient group showed higher functional connectivity between the left intraparietal sulcus and superior temporal and lateral inferior parietal areas. Lateral orbito-frontal areas have been found to be involved in executive processes during working memory tasks, especially during updating processes. The higher involvement of this network in the highly proficient group may indicate that this group of bilinguals more strongly uses updating processes in short-term memory tasks. To sum up, it seems that highly proficient bilinguals activate short-term memory and executive function networks in a more efficient way (Majerus et al., 2008). Another study examined how second language proficiency affects performance monitoring and response inhibition in the oculomotor domain by using a saccadic countermanding task. Performance monitoring was found to be improved in bilinguals with higher second language proficiency suggesting that highly proficient bilinguals benefit from superior cognitive flexibility (Singh & Mishra, 2015). In an ERP study using an non-verbal auditory Go/Nogo task, Fernandez et al. (2013) found that bilinguals showed increased N2 amplitudes which was thought to be related to response suppression, while not showing any differences with monolinguals on the behavioral level. Moreover, second language proficiency was positively correlated with the inhibitory N2 amplitude. These findings were interpreted to indicate that response inhibition may play a role in multiple language use, but if so, an advantage may be hidden by a ceiling effect in young adults but may vary in individuals with different degrees of second language proficiency.

Moreover, longitudinal studies have been conducted in order to investigate the influence of proficiency changes on bilingual language representation and control. Ghazi Saidi et al. (2013) investigated the influence of intense second language vocabulary learning and observed decreased functional connectivity in the control network after the training period compared to the state before vocabulary training when performing an overt picture-naming in their L2. Moreover, reduced functional connectivity between the language and the control network was observed. For the L1 however, no functional connectivity changes were observed. This observation can be interpreted in the way that increased proficiency leads to a higher degree of automaticity and lower cognitive effort

(Ghazi Saidi et al., 2013). Moreover, as for structural changes, higher L2 proficiency has been found to be associated with higher gray matter density in the left inferior parietal cortex (Mechelli et al., 2004) and the left inferior frontal gyrus (Stein et al., 2012), as well as with increased cortical thickness in the right hippocampus and the left superior temporal gyrus (Mårtensson et al., 2012). Furthermore, in intensive language learning L2 proficiency-related laterality shifts in white matter connectivity in the perisylvian language network have been observed (Xiang et al., 2015). In less proficient L2 speakers, structural connectivity in the BA6-temporal pathway (mainly along the arcuate fasciculus) showed a right hemispheric dominance while with increasing proficiency, a stronger left hemispheric dominance emerged (Xiang et al., 2015), for further detail on structural connectivity changes, cf. section 1.4.4. To sum up, higher second language proficiency is relatively robustly found to be associated with higher cognitive control performance, but it is not perfectly clear which control processes are specifically improved with higher proficiency, amongst the most studied processes conflict monitoring, inhibition, cognitive flexibility (involving amongst others switching-related processes such as task engagement and disengagement), etc. Moreover, functional and structural changes in the neurocognitive language, executive control and short-term memory networks point towards a varying degree of involvement of neurocognitive control and memory resources at different proficiencies of L2 processing.

1.5.3. SECOND LANGUAGE IMMERSION EXPERIENCE

An immersion experience in a second language environment, especially initial immersion experience, constitutes a change of constraints on the habitual language use. Considered as environmental enrichment, a language immersion experience probably induces neuronal plasticity in the neuronal networks most involved in dealing with the new situation, i.e. the language and the cognitive control networks. Immersion experience also involves a high degree of implicit language knowledge transmission, which might be beneficial for efficient language acquisition and language learning. For instance, in the long run, immersion has been found to lead to better outcomes in linguistic and metalinguistic skills in the native language as well as the language of immersion (Hermanto et al., 2012) or to an improvement of the proficiency in the language of immersion, potentially at the expenses of ease in L1 processing (Kroll et al., 2010). Moreover, immersion experience is thought to imply specific control demands. Evidence corroborating this idea is that after a five-months immersion experience, increased second language proficiency was shown to be positively correlated with gray matter density change in the left inferior frontal cortex (Stein et al., 2012). Recent findings of a cognitive control advantage with second language immersion also corroborates this idea (Bialystok & Barac, 2012; Nicolay & Poncelet, 2013). However, not only immersion experience, but also intense classroom learning has been shown to lead to structural changes in the language and executive control networks. Increases in cortical thickness of the left middle frontal gyrus, inferior frontal gyrus and superior temporal gyrus as well as increased hippocampal volumes have been found to be after three months of intense language studies (Mårtensson et al., 2012) and a continuous white matter connectivity increase between language areas as well as between frontal regions and the caudate nuclei have been found during intensive 9-months second language training and this pattern of connectivity changes was thought to reflect, amongst others, the involvement of the control network in multiple language control (Schlegel, Rudelson, & Peter, 2012; for a review, see Li, Legault, & Litcofsky, 2014). Moreover, there is evidence not only from the literature on structural connectivity but also from functional studies that there are changes of control involvement with intense language training, i.e. with second language exposure having been shown to lead to changes in ACC activation after only one month’s time (Tu et al., 2015). To conclude, immersion experience and intense classroom learning is often found to be associated with – beyond changes in the language network - structural changes in the neurocognitive control network, indicating specific control demands in immersion.

1.5.4. INTERACTIONAL CONTEXT AND FREQUENCY OF LANGUAGE SWITCHING

Beyond the factors age of acquisition, proficiency and immersion experience, the dominant interactional context – and tightly linked to it the frequency and pattern of language switching - have been claimed to influence bilingual language processing, and in particular the control demands in multiple language use. The interactional context designates the pattern of use of the two or more languages, Green and Abutalebi (2013) as well as Green and Wei (2014) distinguish the *single language context*, i.e. the use of one single language in a given context (work, school, home), the *dual language context*, i.e. the use of different languages with different interlocutors without mixing languages, and *dense code-switching*, i.e. habitual language switching within single conversational turns and intertwining of the morphosyntax of the two languages within sentences. The dominance of one or another of these interactional contexts is largely dependent on the bilingual community (Green, 2011). Green and Abutalebi (2013) argued that each interactional context has different control demands in order to adapt to the constraints of language use, e.g. the dual language context is claimed to be highly demanding in terms of goal maintenance, interference control, selective response inhibition, as well as task engagement and disengagement, in order to keep the two languages separated but to flexibly switch languages with different interlocutors, while dense code-switching is, however, more demanding in opportunistic planning in order to allow for a meaningful intertwining of the morphosyntax of the two languages (Green & Abutalebi, 2013). However, there is some experimental evidence, that the experimental exposure to a mixed compared to a single language context is associated with better performance in non-linguistic control tasks, i.e. the flanker task (Wu & Thierry, 2013). This finding has been interpreted to reflect that the mixed language context shifts the executive system to an enhanced functional level, hence improving the effectiveness of nonverbal conflict resolution (Wu & Thierry, 2013). In a study using a non-verbal task switching paradigm, bilinguals with a higher frequency of daily language switching showed reduced switching costs in a non-linguistic task as compared to bilinguals with a lower frequency of daily language switching as well as monolinguals (Prior & Gollan, 2011). Moreover, the awareness of language switching (intended vs. unintended) has been observed to be related to non-linguistic cognitive control abilities (inhibition; Rodriguez-Fornells, Krämer, Lorenzo-Seva, Festman, & Münte, 2012). The degree of unintended switches was positively correlated to Stop-Signal response times, which indicates that inhibitory control capacity plays a role in the awareness of language switching. Similarly, monitoring performance in non-verbal tasks has been observed to be better in bilinguals with good control over their language switches as compared to those who frequently underwent unintentional language switches (Festman & Münte, 2012). These findings suggest that movement initiation/monitoring processes as well as task engagement and disengagement are involved in bi- and multilingualism and are prone to modulatory effects by efficiency and control over daily language switching as well as by the type of interactional context.

1.5.5. INDIVIDUAL DIFFERENCES BEYOND THE LANGUAGE BACKGROUND IN THE PROPER SENSE

Moreover, Weikum et al. (2013) also found indications for individual differences to cause differences in L2 discrimination ability. Hence, it may be that certain individuals retain greater openness to non-native information than others (Weikum et al., 2013). Other studies directly addressed the question of individual differences in L2 discrimination. Golestani and Zatorre (2009) investigated individual differences in learning to discriminate non-native sounds. Adult participants were tested before and after an adaptive training procedure on their capacity to identify and discriminate non-native Hindi stimuli. The main result was that only half of the participants showed identification performance above chance after training. Splitting between good performers and those performing at chance post-training revealed that the good performers showed above chance discrimination capacity already in the pre-training test while participants performing at chance post-training did also perform at chance before training. Moreover, linguistic experience - as measured by a composite score including the number of languages spoken, respective proficiency and age of acquisition – did not account for these differences. Thus, despite equivalence in their language background, some individuals appear to be better capable of acquiring non-native sounds, but further investigation should also account for the influence of individual differences in sub-processes in realizing the task, such as working memory or strategy differences (Golestani & Zatorre, 2009). A few studies tackled the question of the neuronal underpinnings of these individual differences in phonetic learning capacity. Golestani, Molko, Dehaene, LeBihan and Pallier (2006) found that faster phonetic learners showed increased white matter volume in the left Heschl's gyrus, a part of the brain including the primary auditory cortex, compared to slow learners. Moreover, anatomical differences that may predict language learning – and more specifically phonetic learning – have also been found in areas not typically associated with language processing. For instance, Golestani et al. (2006) found that fast phonetic learners showed higher white matter density in the lingual gyri bilaterally compared to slow learners. The lingual gyri have been found to be involved in visual phonological processing (Burton, LoCasto, Krebs-Noble, & Gullapalli, 2005) and may, according to the findings of Golestani et al. (2006), also play a role in speech sound learning. Hence, white matter connectivity may play a major role in the individual differences in phonetic learning performance. To conclude, beyond the language background of the tested individuals, one should also take into consideration that further factors, such as working memory capacity or strategies in realizing a task, play a role in language processing and control.

2. EXECUTIVE FUNCTIONS: THEORETICAL ACCOUNTS & NEUROFUNCTIONAL MODELS

The emergence and crystallization of research on cognitive control historically coincided with the development of connectionism, with both domains undergoing much progress since the 1980s (Botvinick & Cohen, 2014). However, the initial theoretical foundations of the two fields are considerably different, with initial control research being grounded in principles of symbolic representation, sequential hierarchical processing, and modularity, strongly focusing on the ‘top-down’ processes of control. Subsequently, computational modelling strongly influenced theories of cognitive control. Modelling in this phase strongly took into consideration the role of learning and environmental constraints, hence strongly focused on ‘bottom-up’ processes, and how adaptation takes place in the cognitive control system. Current issues in research on cognitive control concern the questions why the cognitive control structure, involving architecture, representations and operations, and its underlying neuronal substrate are shaped the way they are and how the structure of cognitive control reflects the structure of the task environment, given its role in interaction with naturalistic environments (for a review, see Botvinick & Cohen, 2014). Critically, for understanding human cognitive performance, it is necessary to understand the underlying mechanisms, i.e. the characteristics of the neuronal implementation. The fundamental nature of cognitive processing emerges out of and is shaped by evolutionary and developmental pressures and constraints, including limited capacities of biologically realizable hardware and environmental demands (McClelland et al., 2010).

Current psychological and neurobiological theories conceptualize cognitive control as a unitary instance or as a system fractioned into different subprocesses and again other theoretical accounts try to integrate aspects of both, unity as well as diversity of executive functions. In this latter vein, one of the most cited models has been published by Miyake, Friedman, Emerson, Witzki, Howerter and Wager

(2000) proposing the distinction of three main executive functions, namely inhibition of dominant responses ("inhibition"), shifting of mental sets ("shifting") and monitoring and updating of information in working memory ("updating"; see also the "*unity/diversity* framework" by Miyake & Friedman, 2012). Miyake and Friedman (2012) claim that according to the level executive functions are looked at, one may find shared characteristics amongst the three of the main executive functions (i.e. *inhibition*, *shifting* and *updating*) or one may be able to subdivide each of the functions into more specific control processes. The mentioned executive functions may not be involved to the same degree in every task requiring control (see also, A. Diamond, 2013; Miyake & Friedman, 2012). Looking at the inhibition function more closely, some authors propose a further distinction of inhibitory processes and distinguish, e.g. *active* vs. *automatic inhibition* (Aron, 2007), or *interference suppression* vs. *response inhibition* (Aron, 2007; Bunge, Dudukovic, Thomason, Vaidya, & Gabrieli, 2002; Green & Abutalebi, 2013; Luk, Anderson, Craik, Grady, & Bialystok, 2010). Aron (2007) refers to this latter distinction with the notions *distractor inhibition* (or *selective attention*), on the one hand, and *motor/behavioral inhibition of a physical response*, on the other hand. Experimentally, tasks considered to tap *interference suppression* are the Stroop task (Stroop, 1935), the Simon task (Simon & Ruddell, 1967) or the Erikson flanker task (Eriksen & Eriksen, 1974). On the other hand, *response inhibition* is usually investigated using the Stop-Signal task, the Go/Nogo task, or the antisaccade task (Hallett, 1978). Interference suppression and response inhibition are usually considered as reactive control processes, i.e. control processes that are active in reaction to an external stimulus or signal. However, there is another type of control, i.e. proactive (inhibitory) control, i.e. the endogenous preparation of a response tendency. Proactive inhibitory control leads to a behavioral slowing which facilitates reactive inhibition in case it is needed. Proactive and reactive control processes involve the same neuronal control network and there is a dynamic interplay between these two types of control (Aron, 2011; Jahfari et al., 2012). Increased proactive control reduces the activation for reactive control and vice versa, while both types of control recruit the same network, involving e.g. frontal and parietal areas as well as subcortical structures (Jahfari et al., 2012). Frontal areas that are frequently associated with control functions are the medial frontal ACC and the lateral frontal PFC (Botvinick, Braver, Barch, Carter, & Cohen, 2001; MacDonald et al., 2000; van Veen & Carter, 2002a, 2005). Concerning the relation between frontal areas, notably ACC and PFC, and basal ganglia in cognitive control, it has been claimed that there is a complex interplay between these areas in proactive vs. reactive control. Critically, it has been proposed that in the functional relationship between ACC and PFC (MacDonald et al., 2000), the ACC monitors conflict (or evaluates the expected value of control; Shenhav et al., 2013) and then communicates with the PFC for implementation of control once the need has been identified (Botvinick et al., 2001; MacDonald et al., 2000; Ridderinkhof, Ullsperger, Crone, & Nieuwenhuis, 2004; van Veen & Carter, 2002a, 2005). However, a different account, i.e. the *cascade-of-control model*, postulates a somewhat different relation, in that the PFC imposes a top-down attentional set for task-relevant goals and communicates to the ACC for subsequent response selection and response evaluation (Banich, 2009; Silton et al., 2010).

In an fMRI study, a positive correlation between BOLD in ACC and PFC has been shown (Kerns et al., 2004). However, fMRI BOLD signals reflect metabolic activity associated with neuronal activity, not the neuronal activity itself (Bartels, Logothetis, & Moutoussis, 2008). Consequently, conclusions on the actual neuronal activity in regions and the relation between regions should be drawn with caution and should be related to findings with other neuroimaging and neurophysiological techniques. Recently, not only functional connectivity analyses (i.e. investigating statistical dependencies among remote neurophysiological events, inferred from correlations between measurements of neuronal activity; Friston, 2011) but also effective connectivity analyses (i.e. investigating causal relations between the activity in different neuronal regions; Friston, 2009, 2011) have started to be more widely used and constitute a highly sophisticated approach to study the relation between the activity in different neuronal regions. In effective connectivity measures as implemented in

Dynamic Causal Modelling (DCM; Friston, 2009), a strong positive effective connectivity between two regions indicates that higher activity in the source region leads to higher activity in the target regions of this connection; in the case of negative connectivity, higher activity in the source region leads to reduced activity in the target region (for the notion auf causality in effective connectivity measured using Dynamic Causal Modelling (DCM), see Friston, 2009). In a study investigating effective connectivity in the control network, strong negative connectivity from frontal to subcortical areas was found, which may reflect that increased proactive control leads to reduced need of reactive inhibition (Jahfari et al., 2012). Effective connectivity measures in the connections between specific frontal control areas, i.e. ACC, PFC and pre-SMA, revealed positive and negative connections between these areas, indicating amongst others that there are both, excitatory and inhibitory influences from ACC to PFC (Kouneiher et al., 2009).

In the following sections, the core control processes for evaluating the influence of bilingualism on cognitive control, i.e. *conflict monitoring*, *interference suppression*, *response inhibition* and the switching-related *overcoming of inhibition* will be elaborated. Afterwards, the neurophysiological markers associated with these control processes will be presented (section 2.2). Electroencephalographical (EEG) recordings of event-related potentials (ERPs) allow us to follow with a high temporal resolution, i.e. millisecond by millisecond, the electrical responses of the brain to time-locked events (Coles & Rugg, 1995). In tasks on executive functions, effects at the following ERP components have frequently been found: N2, N4, N2/P3 complex and a late sustained potential. Detailed information on the functional associations of these components is presented in section 2.2.

2.1. CONTROL PROCESSES

In the following, some of the most discussed domain-general control processes that are supposed to play a role in bilingual language control will be presented: *conflict monitoring*, *interference suppression*, *response inhibition* and the switching-related *overcoming of inhibition*. Despite the relevance of other domain-general control processes in language control, this selection consists of the most discussed ones, which are consequently at the core of interest in the subsequently presented experimental part of the present doctoral thesis.

2.1.1. CONFLICT MONITORING

Conflict monitoring has been defined as the process of monitoring for the occurrence of conflict in information processing and is on the evaluative side of cognitive control. Conflict monitoring serves to translate the occurrence of conflict into compensatory adjustments in control, i.e. the conflict monitoring system evaluates the levels of conflict and communicates this information to systems responsible for control implementation (Botvinick et al., 2001). In the ERP literature, conflict monitoring has previously been ascribed to a stimulus-locked fronto-central N2 component, for which evidence has been provided, amongst others, in the Nogo-literature (Donkers & van Boxtel, 2004; Jonkman, 2006; for a review, see Folstein & Van Petten, 2008) and the ACC is considered as a principal neuronal generator (Carter & van Veen, 2007; Folstein & Van Petten, 2008; cf. section 2.2.1).

Several theories of cognitive control distinguish conflict monitoring from inhibitory-related control and their respective underlying sources and neurophysiological markers. However, a strong relation between the two control processes as well as their neuronal underpinnings is usually assumed. The theories of cognitive control proposed by Botvinick (2007) as well as by Carter and Van Veen (2007) postulate a primordial role of the ACC in detecting conflicts while the dorsolateral prefrontal cortex is thought to modulate cognitive control over the suppression of task-irrelevant information. In the same vein, MacDonald, Cohen, Stenger and Carter (2000; see also, Green & Abutalebi, 2013) suggest that a widely distributed neuronal network may be activated in cognitive control processes but that specific subprocesses of control are reflected by spatially and temporally distinguishable activations, i.e. the anterior cingulated cortex (ACC) shows activation in conflict monitoring while the dorsolateral prefrontal cortex (DLPFC) is active in control implementation. Several fMRI studies confirm the crucial role of ACC in detecting, monitoring and processing cognitive conflict as well as in monitoring action outcomes (Botvinick, 2007; Botvinick et al., 2001; Carter et al., 2000; Z. Chen, Lei, Ding, Li, & Chen, 2013; Gruber, Rogowska, Holcomb, Soraci, & Yurgelun-Todd, 2002; Kerns et al., 2004; Leung, Skudlarski, Gatenby, Peterson, & Gore, 2000; Pardo, Pardo, Janer, & Raichle, 1990; Peterson et al., 2002; van Veen & Carter, 2002a, 2005; Yeung, 2013; for a review on the controversial findings in neuropsychological studies, see Yeung, 2013) and in attentional control in cognitive and emotional processes (Bush, Luu, & Posner, 2000; Ochsner, Hughes, Robertson, Cooper, & Gabrieli, 2009). Some fMRI studies have also demonstrated the involvement of dorsolateral prefrontal cortex (DLPFC) activation in tasks evoking cognitive conflict, such as the Stroop task (Z. Chen et al., 2013; MacDonald et al., 2000; Milham, Banich, Claus, & Cohen, 2003; Peterson et al., 2002; van Veen & Carter, 2005). Finally, concerning the role of ACC in conflict processing there are also accounts that challenge the point of view that ACC activation is only involved in conflict monitoring (which is also suggested to be only a part of more diverse conflict evaluation processes). However, the propositions for an alternative functional role of ACC activity are far from univocal; more precisely, it has been claimed that the ACC also plays a role in conflict regulation, which means that the ACC also plays a role in the exertion of control; apart from conflict monitoring, ACC activity of different duration has been suggested to reflect, for instance, task-level conflict, integration of conflict over an extended time or within-trial conflict adaptation (Yeung, 2013).

2.1.2. INTERFERENCE SUPPRESSION

The resistance to distractor interference is the ability to resist or resolve interference from information in the external environment that is irrelevant to the task at hand (Friedman & Miyake, 2004). The capacity to suppress distractor interference is usually assessed using tasks such as the Stroop task (Stroop, 1935), the Simon task (Simon & Ruddell, 1967) or the Erikson flanker task (Eriksen & Eriksen, 1974). In the Stroop task, a color word printed in an incongruent print color is presented to the participant, who usually has to manually or verbally indicate the print color of the stimulus. In this condition, a conflict arises between an automatic process, i.e. word reading, which disturbs a controlled process, i.e. print color naming. Hence, the interfering automatic process needs to be inhibited for correct performance in the task. Alternative accounts state that Stroop is not necessarily to be considered as a task on interference suppression, but that it is rather a task involving response inhibition (Miyake et al., 2000; for a review, see Friedman & Miyake, 2004). Some fMRI studies have also demonstrated the involvement of dorsolateral prefrontal cortex (DLPFC) activation in tasks evoking cognitive conflict, such as the Stroop task (Z. Chen et al., 2013; MacDonald et al., 2000; Milham et al., 2003; Peterson et al., 2002; van Veen & Carter, 2005). In ERP studies, interference suppression is frequently associated with an effect on the N4 component (cf. section 2.2.2) and a late sustained potential (cf. section 2.2.4).

2.1.3. RESPONSE INHIBITION

Prepotent response inhibition is the ability to deliberately suppress dominant, automatic, or prepotent responses (Friedman & Miyake, 2004). Task usually applied in investigating response inhibition capacity are the Stop-Signal task (Logan, 1994), the Go/Nogo task, or the antisaccade task (Hallett, 1978). In ERP studies, the current suppression of the automatic prosaccade in an antisaccade task has been found to be reflected by, amongst others, a target-locked positivity at around 300 ms post-target onset (P3) with parietal distribution which was reduced in anti- compared to prosaccades. The target-locked N2 – interpreted to reflect conflict monitoring or inhibitory processes - and P3 components are also often referred to as the 'N2/P3 complex' and are thought to reflect current suppression of the prosaccade during an antisaccade trial (Mueller, Swainson, & Jackson, 2009).

2.1.4. OVERCOMING OF INHIBITION

Overcoming of inhibition designates the removal of strong inhibition previously applied on a strong distractor or automatic response in order to effectuate a controlled task, when switching towards a simpler task in which no interference suppression or response inhibition is required (for language switching between languages of different dominance, cf. e.g. Meuter and Allport (1999); for non-linguistic task switching, cf. e.g. Mueller et al. (2009)). To study overcoming of inhibition, the negative priming paradigm, initially implemented in a Stroop task by Dalrymple-Alford and Budayr (1966), constitutes a suitable tool (Aron, 2007; for a review and for alternative explications of the negative priming effect, see MacLeod and MacDonald, 2000). As an ERP component, the N2 has been shown to be sensitive to negative priming, and the larger N2 in the negative priming compared to the control condition has been interpreted to reflect the selection of a previously inhibited stimulus against incompatible distractors (Frings & Groh-Bordin, 2007). In an antisaccade task, the transition between the highly automatic prosaccade task and the controlled antisaccade task allow to study overcoming of inhibition in a non-linguistic task (Mueller et al., 2009). In ERP studies, a target-locked late parietal positivity (LPP) with parietal distribution for switch vs. repetition trials has previously been found (Mueller et al., 2009). This component is thought to reflect attentional shifting, i.e. the focusing of attention to the now relevant task (Mueller et al., 2009). The LPP is a component that has not only been found for the antisaccade task but evidence has also been provided from other switching tasks (Rushworth, Passingham, & Nobre, 2002, 2005; Swainson, Jackson, & Jackson, 2006).

2.2. NEUROPHYSIOLOGICAL MARKERS (ERP COMPONENTS) OF EXECUTIVE CONTROL PROCESSES

Electroencephalographical (EEG) recordings of event-related potentials (ERPs) allow us to follow with a high temporal resolution, i.e. millisecond by millisecond, the electrical responses of the brain to time-locked events (Coles & Rugg, 1995). In tasks on executive functions, effects at the following ERP components have frequently been found: N2, N4, N2/P3 complex and a late sustained potential. Detailed information on the functional associations of these components is presented as follows.

2.2.1. N2

The N2 (or N200) component is a negative-going component peaking at around 200 ms after stimulus onset. According to task-specificity and topographical distribution at the surface of the scalp, a distinction of three different subcomponents of the N2 has been suggested (Folstein & Van Petten, 2008). The subcomponents vary in scalp distribution and are thought to reflect different cognitive processes: (1) a fronto-central component reflecting novelty or mismatch, (2) another fronto-central component reflecting cognitive control (response inhibition, response conflict and error monitoring), and (3) a posterior component reflecting some processes of visual attention (for a review, see Folstein & Van Petten, 2008). Concerning the second type - the control-related fronto-central N2 - the anterior cingulate cortex (ACC) has been shown to be a main neural generator (Folstein & Van Petten, 2008; van Veen & Carter, 2002a). ERP studies reported an N2 effect thought to reflect conflict monitoring processes in a Stroop task (Boenke, Ohl, Nikolaev, Lachmann, & Leeuwen, 2009), Simon task (S. Chen & Melara, 2009) or an Erikson flanker task (van Veen & Carter, 2002a); for a review, see Table 1. For the N2/P3 complex frequently found for Go/Nogo, Stop-Signal or antisaccade tasks, see section 2.2.3. Moreover, the N2 component has also been observed to be sensitive to negative priming. The N2 amplitude was larger in negative priming (the distractor in the preceding trial becomes the target in the current – negative priming – trial) compared to control trials and this effect is thought to reflect the selection of a previously inhibited stimulus against incompatible distractors (Frings & Groh-Bordin, 2007). Moreover, an N2 effect has also been found to be related to cognitive control in tasks involving a linguistic component. In language switching tasks, an increased N2 was observed in a task implying language switching in both directions (Chauncey, Grainger, & Holcomb, 2008). Similarly, in a production task, a larger N2 was demonstrated for language switching in one switching direction (L1 to L2; G. M. Jackson, Swainson, Cunnington, & Jackson, 2001; for a review, see Van Hell & Wittemann, 2009). In Table 1, an overview of studies documenting an N2 effect in cognitive control tasks will be given. For N2 effects habitually appearing in combination with a P3 effect, cf. section 2.2.3 concerning the N2/P3 complex.

Table 1. The functional interpretation of the N2 effect in tasks involving cognitive control. Time window indicates the time window of an observed effect on the N2 component. ACC, anterior cingulate cortex; IFC, Inferior-frontal cortex; MCC, midcingulate cortex.

N2 effect in tasks involving cognitive control					
Reference	**Paradigm**	**Time window**	**Surface topography**	**Functional attribution**	**Neuronal generator**
Boenke et al. (2009)	Stroop	268–360	Fronto-central	Cognitive control processes involved in conflict detection and monitoring	Medial frontal cortex, including ACC
Chen & Melara (2009)	Simon	360-400	Central	Working memory; disruption in working memory due to Stimulus-Response (S-R) conflict; conflict in information held in working memory	-

Enriquez-Geppert et al. (2010)	Combined Go/Nogo - Stop-Signal task	20 ms around peak in window 200-350;	Fronto-central	Conflict monitoring	IFC, MCC
Frings & Groh-Bordin (2007)	Negative priming	170-270 (P2/N2 complex)	Frontal, fronto-polar	Selection of previously inhibited stimulus against incompatible distractors	-
Jackson et al. (2001)	Language switching	Peak at 320 ms after stimulus onset	Fronto-central	Inhibitory processes (response suppression similar to inhibition in a Go/Nogo task) during language switching	-
Melara et al. (2008)	Simon	175–325	Fronto-central	Attentional disruption caused by S-R conflict in working memory	-
Naylor et al. (2012)	Between-within language Stroop	200-350	Fronto-central	A stage in conflict processing/inhibitory control parallel to N4 that facilitate the resolution of conflict at the LSP (late sustained potential, cf. section 2.2.4)	-
Nieuwenhuis et al. (2003)	Go/Nogo	250-350	Fronto-central	(Response) conflict monitoring	ACC
van Veen & Carter (2002b)	Flanker	340-380	Fronto-central	Conflict detection	ACC
Yeung & Nieuwenhuis (2009)	Flanker	Negative peak ~300 ms after stimulus onset	Fronto-central	Conflict monitoring	Medial frontal cortex, including ACC

2.2.2. N4

The N4 (or N400) component is a negative-going component at posterior sites peaking at around 400 ms after stimulus onset. This ERP component has first been shown by Kutas and Hillyard (1980) as reflecting processing of semantic incongruities during the visual integration of words in English sentences. An N4 effect, i.e. a more negative amplitude in a (usually semantically) incongruent as compared to a congruent condition is habitually found in the time window 200-600 ms after stimulus onset and is largest over centro-parietal sites. The amplitude of the N4 component is thought to be related to meaning processing and is sensitive to a range of linguistic and non-linguistic stimuli (Kutas & Federmeier, 2011). The N4, especially variations in its amplitude, have been associated with a variety of neurocognitive functions and processes, such as lexical-semantic integration in sentences (Kutas & Hillyard, 1980), lexical access (Van Petten & Kutas, 1990), binding (Federmeier & Laszlo, 2009), orthographic/phonological analysis (Deacon, Dynowska, Ritter, & Grose-Fifer, 2004), semantic memory access (Kutas & Federmeier, 2000; Van Berkum, 2009) or semantic/conceptual unification (Hagoort, Peter, Baggio, & Willems, 2009; for a review, see Kutas & Federmeier, 2011). It is to be noted, that in addition to ERP markers such as the N4, oscillatory firing patterns, which reflect complex dynamic interactions of cell populations, can be important markers for semantic and multisensory information integration in the brain (Engel, Senkowski, & Schneider, 2012; Hagoort, Hald, Bastiaansen, & Petersson, 2004; Schneider, Debener, Oostenveld, & Engel, 2008). In psycholinguistics, the N4 is a neurophysiological marker that can be used for examining almost every aspect of language processing (Kutas & Federmeier, 2011), but is best known for its sensitivity to semantic anomalies (Kutas & Hillyard, 1980; for a review, see Kutas & Federmeier, 2011). However, the sensitivity of the N4 is not limited to language processing but has been found to be sensitive to contextual incongruency in both, linguistic processing (with semantic context sensitivity found on both, the local (sentence) and the global (discourse) level; Van Berkum, Zwitserlood, Hagoort, & Brown, 2003; Willems, Özyürek, & Hagoort, 2008) as well as non-linguistic, i.e. picture, processing (Willems et al., 2008). Hence, the N4 has recently shifted from a marker of language processing towards a marker of meaning processing more broadly, and is applicable in e.g. object and face recognition, as well as action and gesture processing (Kutas & Federmeier, 2011). The meaning of a stimulus is not computed at a single point in time but something that emerges though time; the activity measured in the N4 represents an important aspect in this emergent process but not the final state (Kutas & Federmeier, 2011).

Moreover, an N4 effect has also been found to be related to cognitive control in tasks involving a linguistic component. In language switching tasks, an N4 effect has been found for inhibitory processes. More precisely, in comprehension tasks a larger N4 was found for switching compared to non-switching conditions, either in one switching direction (L1 to L2; Alvarez, Holcomb, & Grainger, 2003) or in both directions (L1 to L2 and L2 to L1; Chauncey et al., 2008; Proverbio, Leoni, & Zani, 2004). Furthermore, an N4 effect was also observed in several EEG studies examining temporal dynamics underlying the interference arising in the Stroop task (Stroop, 1935). This effect reflects a larger negativity in the incongruent condition in comparison to the congruent condition or a neutral condition (a non-color word or a string of signs written in one of the print colors; Appelbaum, Meyerhoff, & Woldorff, 2009; Badzakova-Trajkov, Barnett, Waldie, & Kirk, 2009; Bruchmann, Herper, Konrad, Pantev, & Huster, 2010; Coderre, Conklin, & van Heuven, 2011; Hanslmayr et al., 2008; Liotti, Woldorff, Perez III, & Mayberg, 2000; Naylor et al., 2012; Qiu, Luo, Wang, Zhang, & Zhang, 2006; West, 2003); for a review, see Table 2. However, it remains unclear whether this component is the same as the classic N4 first identified by Kutas and Hillyard (1980; Silton et al., 2010). The so-called N4 Stroop effect usually mirrors the behavioral Stroop effect, i.e. longer response times in the incongruent compared to the congruent condition, response times to neutral stimuli lying in between. A larger negative deflection in the incongruent compared to the congruent and neutral conditions in the time window 400-500 ms post stimulus onset (N4 effect) is interpreted to sign the higher cognitive cost in responding to stimuli in the incongruent condition – usually causing a conflict between the two sources of information, the color word and the print color. Some studies investigating the localization of the main neuronal generator of the N4 Stroop interference effect have shown that the difference of N4 amplitude between the incongruent and congruent conditions mainly originates in the ACC (Badzakova-Trajkov et al., 2009; Bruchmann et al., 2010; Hanslmayr et al., 2008; Liotti et al., 2000; Markela-Lerenc et al., 2004) and the prefrontal cortex (PFC; Badzakova-Trajkov et al., 2009; Bruchmann et al., 2010; Hanslmayr et al., 2008; Liotti et al., 2000; Markela-Lerenc et al., 2004; Qiu et al., 2006). In Table 2, a review of the functional interpretation of the N4 effect in the Stroop task and related tasks requiring cognitive control will be given.

Table 2. The functional interpretation of the N4 effect in tasks involving cognitive control. Time window indicates the time window of an observed effect on the N4 component. ACC, anterior cingulate cortex; PFC, prefrontal cortex.

N4 effect in tasks involving cognitive control					
Reference	**Paradigm**	**Time window**	**Surface topography**	**Functional attribution**	**Neuronal generator**
Appelbaum et al. (2009)	Stroop	450-500	Centro-parietal	Central executive control processes (detection and/or resolution of response conflict); semantic incongruency	ACC (posterior part), left parietal regions
Badzakova-Trajkov et al. (2009)	Stroop	370-480	Centro-parietal	Attentional allocation/conflict identification and resolution	ACC
Bruchmann et al. (2010)	Stroop	396-576	Centro-parietal	Conflict monitoring and processing	ACC, right PFC
Coderre et al. (2011)	Stroop	400-500	Centro-parietal	Conflict detection	ACC
Frings & Groh-Bordin (2007)	Negative priming	330-420	Left-lateralized	Enhanced semantic processing	-
Hanslmayr et al. (2008)	Stroop	400-500	Fronto-central	Interference detection and elicitation of central executive processes (rather than semantic incongruency)	ACC
Larson et al. (2009)	Stroop	Voltage at the most negative peak between 350 and 500 ms (420-440)	Fronto-medial	Conflict monitoring processes	-
Liotti et al. (2000)	Stroop	350-500	Medial-dorsal	Suppression or overriding the processing of the incongruent word meaning	Dorsal ACC
Markela-Lerenc et al. (2004)	Stroop	350-450	Left fronto-central	Conflict monitoring, control implementation	Left inferior PFC, ACC
Naylor et al. (2012)	Between-within language Stroop	350-550	Medial-central	A stage in conflict processing/inhibitory control parallel to N2	-
Qiu et al. (2006)	Stroop	350-550	Fronto-central	Conflict processing, response selection	PFC
West (2003)	Stroop	450-500	Parietal	Conflict detection	ACC, left frontal cortex
West et al. (2005)	Stroop, counting, digit-location tasks	400-450	Negative deflection: central	Conflict processing	-

2.2.3. P3 - N2/P3

The P3[6] (or P300) component is a positive-going waveform at around 250-500 ms after stimulus onset with a centro-parietal distribution and a P3 effect is regularly found in tasks requiring inhibitory control (Polich, 2007). The P3 amplitude has been observed to be smaller with increasing resource allocation (Polich, 2007) and task complexity (Gajewski & Falkenstein, 2013; Maguire et al., 2009). Moreover, the P3 latency corresponds to stimulus evaluation time and increases with task difficulty, e.g. in a semantic categorization task (Kutas, McCarthy, & Donchin, 1977) or in a Go/Nogo task with a varying degree of conceptual-semantic information necessary to respond correctly (Maguire et al., 2009). The P3 is frequently documented in the combination with an N2 effect, hence forming an N2/P3 complex. In a review on response inhibition tasks, i.e. principally the Go/Nogo and Stop-Signal tasks and closely related paradigms, Huster et al. (2013) conclude that the underlying processes in the Go/Nogo and Stop-Signal tasks basically rely on the same cognitive constructs, i.e. the same processes of response inhibition. As the most robust electrophysiological marker in response inhibition tasks emerges the N2/P3 complex, with the N2 reflecting mismatch or cognitive control processes and the P3 updating and inhibition (Huster et al., 2013). However, it has also been argued that the P3 usually peaks after the actual behavioral response, which indicates that the P3 may not be an indicator of the inhibitory process itself but may rather reflect an aftereffect of inhibition, such as the evaluation of inhibitory performance (K. J. Bruin, Wijers, & van Staveren, 2001; Gajewski & Falkenstein, 2013). The main neuronal generator of the N2 seems to be a medial source, most likely localized in the midcingulate cortex (Huster et al., 2013; van Veen & Carter, 2002a). The neuronal generators of the P3 are however localized in a widely distributed system, including temporo-parietal, insular, pre-central and mid-frontal regions (Huster et al., 2013).

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[6] Moreover, two subcomponents of the P3 can be distinguished: the P3a and the P3b. The P3a originates from stimulus-driven frontal attention mechanisms, whereas the P3b originates from temporal-parietal activity associated with attention and appears related to subsequent memory processing (Polich, 2007).

The N2/P3 complex has been found for tasks involving response inhibition, e.g. the Go/Nogo task (Enriquez-Geppert et al., 2010; S. R. Jackson, Jackson, & Roberts, 1999; Lavric, Pizzagalli, & Forstmeier, 2004; Moreno et al., 2014), the Stop-Signal task (Huster et al., 2011), or the antisaccade task (Mueller et al., 2009), but also in tasks involving interference suppression, e.g. the Stroop task (Boenke et al., 2009; Kousaie & Phillips, 2012b), the Simon task (Leuthold, 2011), the flanker task (Kousaie & Phillips, 2012b), and a partially incongruent categorization task (A. Chen et al., 2008). In the N2/P3 complex, the N2 effect usually consists of a larger N2 amplitude in the incongruent compared to the congruent condition, and the subsequent P3 effect consists of a reduced P3 amplitude in the critical (e.g. incongruent) compared to the control (e.g. congruent) condition in tasks involving interference suppression or response inhibition (A. Chen et al., 2008; S. R. Jackson et al., 1999; Kousaie & Phillips, 2012b; Mueller et al., 2009), or, in contrast, of an increased P3 amplitude in the critical (e.g. nogo or stop) as compared to the control (e.g. go) condition, usually in tasks involving response inhibition (Enriquez-Geppert et al., 2010; Huster et al., 2011; Moreno et al., 2014). Note that the P3 effect found in interference tasks, in most cases the Stroop task, is supposed to be equivalent to what is labelled 'N4 effect' by different authors[7] (see also section 2.2.2). Concerning the antisaccade task, it has been claimed that this task involves not only the need to inhibit an automatic response but also to change a response pattern ('vector inversion'; Munoz & Everling, 2004), which constitutes a qualitative difference compared to the response pattern in simple nogo or stop tasks (Huster et al., 2013). Similarly, Barton et al. (2005) argued that the inhibitory processes in the antisaccade and Go/Nogo paradigms seem to be identical, while in the antisaccade task additional control mechanisms are required, potentially linked to vector inversion.

To conclude, based on previous evidence one can argue in favor of a functional separation of the N2 effect (conflict monitoring) and the P3 effect (inhibition). However, the two effects have also

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[7] "In some cases, N450 manifests as a negative peak, clearly distinct from and later than the central N2, maximal at frontocentral electrodes but extending to parietal electrodes, where it appears as a negative deflection of the P3." (Folstein & Van Petten, 2008, p. 182)

been observed not to be mutually exclusive and it remains to be studied whether the slight overlap between the two effects is a physiological side-effect due to neuronal mass activity and its volume conduction or if it reflects a true interaction of cognitive processes, that might already be found at the conceptual level (Enriquez-Geppert et al., 2010). Hence, the relation between effects observed on the N2 and the P3 components and the interaction between their underlying sources remains to be further elucidated. Finally, for the N2/P3 complex in a Go/Nogo task, an increased N2 nogo amplitude and an increased N2 effect (nogo vs. go) has been found in groups with specific expertise, i.e. bilinguals (Moreno et al., 2014). On the other hand, in a continuous performance test (CPT) – a task that is similar to a Go/Nogo paradigm - reduced N2 and P3 amplitudes were found in patient groups having suffered head trauma (Duncan, Kosmidis, & Mirsky, 2005). In Table 3, a short overview of studies documenting an N2/P3 complex in tasks involving cognitive control will be given.

Table 3. The functional interpretation of the N2/P3 complex in tasks involving cognitive control. Time window indicates the time window of an observed effect on the N2 or P3 component. ACC, anterior cingulate cortex; IFC, Inferior-frontal cortex; MCC, midcingulate cortex; PFC, prefrontal cortex; pre-SMA, pre-supplementary motor area.

N2/P3 effect in tasks involving cognitive control					
Reference	**Paradigm**	**Time window**	**Surface topography**	**Functional attribution**	**Neuronal generator**
Boenke et al. (2009)	Stroop	N2: 268–360 (N2 was observed on ascending slope of P3); P3: -	N2: fronto-central; P3: frontal, temporal and parietal areas	N2: cognitive control processes involved in conflict detection and monitoring; P3: -	N2: medial frontal cortex, including ACC; P3: -
Chen et al. (2008)	Partially incongruent categorization task	N2: 240-300; P3: 340-400	N2: fronto-central; P3: fronto-central (right lateralized)	N2: conflict detection; P3: inhibitory control	N2: ACC; P3: right inferior PFC
Enriquez-Geppert et al. (2010)	Combined Go/Nogo - Stop-Signal task	N2: 20 ms around peak in window 200-350; P3b: 20 ms around peak in window 300-	N2: fronto-central; P3: fronto-central	N2: conflict monitoring; P3: response suppression / motor inhibition	N2: IFC, MCC; P3: IFC

		450			
Huster et al. (2011)	Stop-Signal	N2: 150-250; P3: 250-500	N2: fronto-central; P3: fronto-central	N2: conflict monitoring; P3: suppression and slowing of motor behavior	N2: MCC; P3: basal ganglia, aMCC, pre-SMA, anterior insula
Jackson et al. (1999)	Go/Nogo	N2: ~150-200; P3: ~ 350	N2: frontal; P3: posterior parietal	N2: associated with the withholding of a manual response; P3: decision to withhold the execution of a motor response	N2: IFC; P3: posterior parietal cortex
Kousaie & Phillips (2012b)	Stroop	N2: 220-360; P3: 300-500	N2: fronto-central; P3: central	N2: conflict monitoring; P3: resource allocation	-
Kousaie & Phillips (2012b)	Simon	N2: -; P3: 240-460	N2: -; P3: central	N2: -; P3: resource allocation, stimulus categorization	-
Kousaie & Phillips (2012b)	Eriksen Flanker	N2: 260-420; P3: 300-560	N2: central; P3: central	N2: conflict monitoring; P3: stimulus categorization	-
Krämer et al. (2011)	Stop-Signal including a signal to change motor program	N2: 220-280; P3: 300-400	N2: frontal; P3: parietal	N2: inhibition (N2 effect absent in change trials); P3: possibly subcomponents of this late positivity are associated with stimulus evaluation on the one hand and the cognitive response selection process on the other hand	-
Lavric et al. (2004)	Go/Nogo	N2: 235–256; P3: -	N2: fronto-cental; P3: -	N2: inhibition; (P3 (frontal): relative novelty)	N2: ventral (vPFC), dorsolateral PFC (dlPFC); vPFC-dlPFC connectivity, ACC-PFC connectivity; P3: -
Maguire et al. (2009)	Go/Nogo involving conceptual-semantic component	N2: 150-300; P3: 300-600	N2: frontal; P3: central	N2: inhibitory processing; P3: inhibition, interaction between inhibition and conceptual-semantic processing	-
Melara et al. (2008)	Simon	N2: 175–325; P3: 280–450	N2: frontal-central; P3: central	N2: attentional disruption caused by S-R conflict in working memory; P3: conflict resolution	-
Moreno et al. (2014)	Go/Nogo	N2: 270–320; P3: 350-500	N2: fronto-central; P3: centro-parietal	N2: conflict detection or inhibition; P3: closure of the inhibition of the overt response or ongoing evaluation of the intention to inhibit	-
Mueller et al. (2009)	Antisaccade task	N2: 180–244; P3: 292–492	N2: parietal; P3: parietal	N2/P3: current inhibition	-

2.2.4. LATE SUSTAINED POTENTIAL (LSP)

In several neurophysiological studies using a Stroop task, one further ERP component was found in the time window of about 550 – 800 ms, that is a sustained fronto-central negative-going potential, i.e. a late sustained potential (LSP[8]; Hanslmayr et al., 2008; Naylor et al., 2012; West, 2003). Note that some studies also found an additional centro-parietal positive deflection in the incongruent compared in the congruent condition (Appelbaum et al., 2009; Coderre et al., 2011; Hanslmayr et al., 2008; Liotti et al., 2000; West, 2003). The sustained centro-parietal positivity and/or frontal negativity was discussed to reflect either engagement of executive processes (Hanslmayr et al., 2008), conflict resolution processes (Coderre et al., 2011; Naylor et al., 2012; West, 2004), semantic reactivation of the meaning of words following conflict resolution (Appelbaum et al., 2009; Liotti et al., 2000) or response selection (West, 2003, 2004). Source localization has rarely been done for this late sustained negative-going potential but there is some evidence of its main neuronal generators in the middle or inferior frontal gyrus and the extrastriate cortex (West, 2003). In Table 4 a brief overview of studies documenting a late sustained potential in tasks involving cognitive control will be given.

Table 4. The functional interpretation of the LSP (late sustained potential) effect in tasks involving cognitive control. Time window indicates the time window of an observed effect on the LSP component. ACC, anterior cingulate cortex.

LSP effect in tasks involving cognitive control					
Reference	**Paradigm**	**Time window**	**Surface topography**	**Functional attribution**	**Neuronal generator**
Appelbaum et al. (2009)	Stroop	850-900	Positive deflection: parieto-occipital	Processing of semantic meaning of words	-
Chen & Melara (2009)	Simon	480–520	Positive deflection: parietal	Maintenance of current stimulus-response relations in working memory rather than conflict resolution	-

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[8] Note that this component has varying names with the different authors, e.g. late negativity (LN; Hanslmayr et al., 2008), sustained negativity (SN; Naylor et al., 2012), or conflict sustained potential (SP; West, 2003).

Coderre et al. (2011)	Stroop	600-900	Positive deflection: Centro-parietal	Conflict resolution or post-resolution processes	-
Hanslmayr et al. (2008)	Stroop, Negative priming	600-800	Negative deflection: fronto-central; Positive deflection: parieto-occipital	Engagement of central executive processes	ACC
Larson et al. (2009)	Stroop	650-850	Positive deflection: parietal	Conflict processing (conflict resolution processes)	-
Liotti et al. (2000)	Stroop	500-800	Negative deflection: anterior frontal; Positive deflection: Left superior temporo-parietal scalp	Reactivation of the meaning/ Retrieval of semantic meaning of the incongruent word	Left posterior generator(s) (left temporo-parietal cortex)
Markela-Lerenc et al. (2004)	Stroop	600-1000	Positive deflection: parietal	-	-
Naylor et al. (2012)	Between-within language Stroop	550-700	Negative deflection: fronto-central	Conflict resolution (possibly facilitated by efficient N2 inhibitory control processes)	-
West (2003)	Stroop	750-850	Negative deflection: lateral-frontal; Positive deflection: centro-parietal	Conflict processing	Middle or inferior frontal gyrus, left extrastriate region
West et al. (2005)	Stroop, counting, digit-location tasks	600-700	Negative deflection: lateral-frontal; Positive deflection: parietal	Response selection rather than conflict resolution	-

2.3. EYE MOVEMENT CONTROL: THE ANTISACCADE TASK

The antisaccade task is a task that allows for studying the volitional control of action (Munoz & Everling, 2004). The suppression and/or generation of saccadic eye movements involves activation in a number of cortical and subcortical structures (Figure 3), i.e. the dorsolateral prefrontal cortex (DLPFC), the anterior cingulate cortex (ACC), the lateral intraparietal area (LIP), the supplementary eye fields

(SEF), the frontal eye fields (FEF), the superior colliculus (SC), the substantia nigra pars reticulata (SNpr; Munoz & Everling, 2004), the striatum (Aron, 2011) and the thalamus (for reviews, see Aron, 2011; McDowell, Dyckman, Austin, & Clementz, 2008; Munoz & Everling, 2004). In preparatory stages, at the time when the instructional cue indicates that an antisaccade needs to be prepared, the activity of fixation neurons in the FEF and SC is enhanced while the activity of saccade neurons is reduced, as compared to the cueing for a prosaccade. This in part explains the longer response times for antisaccades than for prosaccades (Munoz & Everling, 2004). During antisaccades, the automatic activation of saccade neurons contralateral to the visual target needs to be inhibited while saccadic activity ipsilateral to the stimulus (contralateral to the target movement) is required. In the antisaccade task, *conflict monitoring* is required (Botvinick et al., 2001; Nieuwenhuis, Broerse, Nielen, & Jong, 2004) because the requirement to look away from a visual stimulus creates a conflict between two opposing saccade commands, an automatic (sensory-driven) saccade toward the stimulus and a voluntary (internally driven) saccade away from the stimulus (Watanabe & Munoz, 2009). The *inhibition* of saccade neurons is probably carried out by fixation neurons and interneurons in the FEF and SC, which receive the information to do so probably from the SEF, the DLPFC, or the SNpr. The neuronal underpinnings of *vector inversion*, which is required for carrying out correct antisaccades beside *inhibition*, are not yet very well understood but there is evidence that the LIP – which is at the interface between sensory and motor processing – and the FEF play a role in this process. Moreover, the anterior cingulate cortex (ACC) has been found to play a role in reflexive saccade suppression (McDowell et al., 2008; Paus, 2001) and is thought to be active during *conflict monitoring* processes involved in antisaccade trials (Botvinick et al., 2001; Carter & van Veen, 2007; McDowell et al., 2008; van Veen & Carter, 2002a). Once a pro- or antisaccade are initiated, fixation neurons in the FEF and SC cede to fire and there is a buildup of activity in saccade neurons.

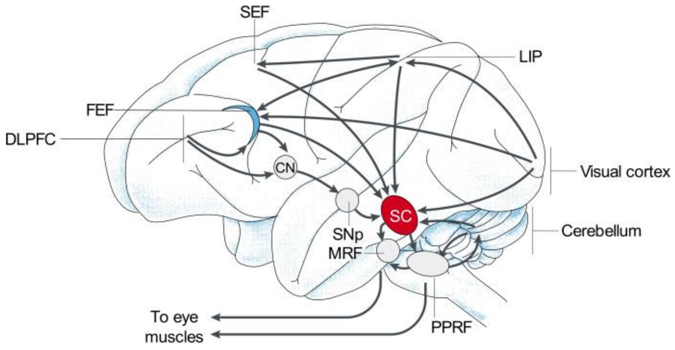


Figure 3. Saccadic eye movements and oculomotor neurophysiology (Fecteau & Munoz, 2003). ACC, anterior cingulate cortex; CN, caudate nucleus; DLPFC, dorsolateral prefrontal cortex; FEF, frontal eye field; LIP, lateral intraparietal area; MRF, medullary reticular formation; PPRF, paramedian pontine reticular formation; SC, superior colliculus; SEF, supplementary eye fields; SNp, substantia nigra pars reticulata**.** (Reprinted by permission from Macmillan Publishers Ltd: Nature Reviews Neuroscience; Fecteau and Munoz, 2003; copyright 2003; http://www.nature.com/nrn/journal/v4/n6/full/nrn1114.html)

The antisaccade task is a task that allows for studying the volitional control of action (Munoz & Everling, 2004). Participants are instructed to carry out either an automatic eye movement towards a visual target (prosaccade) or suppress this automatic eye movement and effectuate a saccade into the opposite direction (antisaccade), depending on the color of the instructional cue preceding the target stimulus. Miyake and Friedman (2012) classify the antisaccade task as a representative task to study *inhibition*, with *inhibition* defined as the "deliberate overriding of dominant or prepotent responses". More specifically, it is the processes of *response inhibition* that is supposed to be involved in an antisaccade task, given that an extremely prepotent, i.e. a reflexive response, the automatic prosaccade, needs to be inhibited (Luna, 2009; there is some experimental evidence for a separation between response inhibition and interference suppression, see e.g. Bunge, Dudukovic, Thomason, Vaidya, & Gabrieli, 2002). Munoz and Everling (2004), however, claim that the antisaccade task does not only require inhibition of the automatic prosaccade but also *vector inversion*, i.e. the stimulus vector must be inverted into the saccade vector in order to initiate a voluntary antisaccade (see also, Collins, Vergilino-Perez, Delisle, & Dore-Mazars, 2008). Moreover, it has been suggested that *conflict monitoring* is a relevant control process for successful antisaccade performance (Botvinick et al., 2001; Nieuwenhuis et al., 2004). *Conflict monitoring* has been defined as the processes of monitoring for the occurrence of conflict in information processing and is on the evaluative side of cognitive control. *Conflict monitoring* serves to translate the occurrence of conflict into compensatory adjustments in control, i.e. the conflict monitoring system evaluates the levels of conflict and communicates this information to systems responsible for control implementation (Botvinick et al., 2001). *Monitoring* is thought to be a subprocess of *updating*, one of the three main executive functions (*inhibition*, *shifting*, *updating*; Miyake & Friedman, 2012). Finally, the ability to *switch* between different task-sets illustrates the *shifting* component of executive functions which reflects the flexibility and ease of transitioning to new task-set representations (Miyake & Friedman, 2012). The *switching* process involves task disengagement, task engagement, suppression of previous task sets (Green & Abutalebi, 2013; Koch, Gade, Schuch, & Philipp, 2010; Monsell, 2003), overcoming of inhibition and attentional shifting (Mueller et al., 2009). When the direction of switch is from a more difficult towards an easier task, previously applied sustained inhibition needs to be overcome, which is not the case in switching from the easier to the more difficult task. This difference in processing requirements leads to the larger switching costs in switching towards the easier than towards the more difficult task (respectively when switch trials are compared to repetition trials), which produces the robustly observed asymmetrical switching effect (Mueller et al., 2009; for a review on the overcoming of inhibition and alternative accounts to explain asymmetrical switching costs, see Monsell, 2003).

3. OBJECTIVES AND HYPOTHESES OF THE PRESENT RESEARCH

The goal of the present doctoral thesis is to examine the relation between bi- or multilingualism and cognitive control processes. The significance of the present project lies in the contribution to our understanding of the cognitive and neuronal dynamics of domain-general executive control involvement in bilingual language processing. In studying the neurodynamics underlying linguistic and non-linguistic control in bilinguals and monolinguals, it is aimed to investigate (1) whether domain-general control processes are involved in bilingual language control, and if this is the case, (2) which these processes are, (3) how they are implemented at the neuronal level, and especially (4) how they are related and influence each other. This research is aimed at contributing to our understanding of neuroplastic changes during sustained multiple language use and to the changes in network neurodynamics underlying strengthened domain-general executive control. The sustained possibility of suffering interferences between languages is inherent to the bilingual experience of multiple language use and is thought to lead to a reinforcement of conflict monitoring and inhibitory control in order to meet communicatory requirements in both languages. Indeed, one major function of language is to enable an effective communication between interlocutors, which underlies the cognitive capacity to maintain a goal in one appropriate language, that means to use a specific language in a specific interactional context, and to maximally limit inappropriate grammatical (negative) transfers from one language, in general from the more automatic one, to the other language, in general the less automatized one. Moreover, we approached the question of the sharing of executive control processes by different domains by investigating how bilinguals are able to perform linguistic and nonlinguistic (motoric) tasks which all involve the control of interferences. It is aimed to gain further insight into the neurodynamics of the neuronal underpinnings of domain-general executive control involvement in bilingual language, while taking into consideration the heterogeneity of bilingualism in considering the relevance of linguistic background variables.

The significance and novelty of the present doctoral work lies in the contribution to our understanding of the cognitive and neuronal dynamics of domain-general executive control involvement in bilingual language processing by attempting to disentangle the different control processes that may benefit from an advantage of the regular use of a foreign language. In studying the neurodynamics underlying linguistic and non-linguistic control in bilinguals and monolinguals, it is aimed to investigate if and which domain-general control processes are involved in bilingual language control and hence become strengthened and how these processes are reflected on the neuronal level. Moreover, in studying the cognition and the dynamics in the neuronal underpinnings of control over multiple language use it is not only of interest, which processes play a role but how they are related and influence each other. This research work contributes to our understanding of neuroplastic changes during sustained multiple language use and to the changes in network neurodynamics underlying strengthened domain-general executive control.

PART 2: EXPERIMENTAL WORK

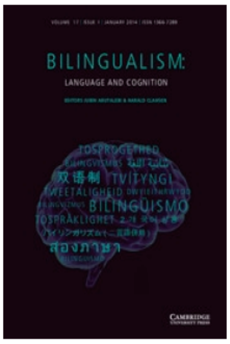
In the experimental part of the present doctoral thesis, three studies will be presented: Section 4 will deal with the impact of bilingualism in tasks involving a linguistic component, i.e. a Stroop task and the negative priming paradigm. More precisely, in section 4.1, the study entitled *Successive bilingualism and executive functions: The effect of second language use on inhibitory control in a behavioural Stroop Colour Word task* (Heidlmayr, Moutier, Hemforth, Courtin, Tanzmeister, & Isel, 2014), a behavioral study on a Stroop task will be presented. This study also has a strong focus on the role of the language background factors immersion experience as well as the frequency of second and third language use in bilingual language control. In section 4.2, the study entitled *Neurodynamics of executive control processes in bilinguals: Evidence from ERP and source reconstruction analyses* (Heidlmayr, Hemforth, Moutier, & Isel, 2015) will be presented. This neurophysiological study using a combined Stroop and negative priming task investigates the neurodynamics of control processes at the scalp and source level and also investigates the modulatory influence of language background measures on control efficiency. Then, section 5 will present research on the influence of bilingualism on conflict processing in a non-linguistic task, i.e. the antisaccade task. In section 5.1 the study entitled *Multiple language use influences oculomotor task performance: Neurophysiological evidence of a shared substrate between language and motor control* (Heidlmayr, Doré-Mazars, Aparicio, & Isel, submitted), a neurophysiological study investigating the neurodynamics of control processes at the scalp and - in the form of effective connectivity analyses - at the source level will be presented. Moreover, in this study the experimental measures are put in relation with language background measures, e.g. immersion experience or L2 proficiency. Finally, section 6 will present the General Discussion of the experimental work in the present doctoral thesis, followed by the conclusions in section 7 and the future research perspectives in section 8.

4. CONTROL IN TASKS INVOLVING A LINGUISTIC COMPONENT

4.1. STUDY 1: BEHAVIORAL STUDY USING A STROOP TASK

In Study 1 (Heidlmayr, Moutier, Hemforth, Courtin, Tanzmeister, & Isel, 2014; copyright Cambridge University Press 2013; reprinted with permission) it was aimed to study the impact of bilingualism on cognitive control in an executive control task involving a linguistic component, i.e. the Stroop task. Moreover, we aimed at investigating the role of specific linguistic background parameters on cognitive control of linguistic interference. Hence, the linguistic background was assessed for all bilingual and monolingual participants and in bilingual participants, the environment of language immersion was manipulated, i.e. half of the bilingual participants were resident in their L1 environment, France, while the other half were resident in their L2 environment, Germany or Austria.

This behavioral study using the Stroop task allowed for investigating top-down inhibitory control efficiency in two populations of bilinguals. Bilinguals passed the Stroop task in both, their L1 and L2, which allowed for investigating control of linguistic interference in their more dominant L1 and the less dominant L2. We hypothesized that the frequency of L2 use as well as the duration of second language use, amongst others, would modulate the efficiency of inhibitory control involvement in the Stroop task and that the Stroop interference would be smaller in the L2 than the L1, given the reduced automaticity of the late learned L2 in comparison to the L1.



Successive bilingualism and executive functions: The effect of second language use on inhibitory control in a behavioural Stroop Colour Word task

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Successive bilingualism and executive functions: The effect of second language use on inhibitory control in a behavioural Stroop Colour Word task*

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Here we examined the role of bilingualism on cognitive inhibition using the Stroop Colour Word task. Our hypothesis was that the frequency of use of a second language (L2) in the daily life of successive bilingual individuals impacts the efficiency of their inhibitory control mechanism. Thirty-three highly proficient successive French–German bilinguals, living either in a French or in a German linguistic environment, performed a Stroop task on both French and German words. Moreover, 31 French monolingual individuals were also tested with French words. We showed that the bilingual advantage was (i) reinforced by the use of a third language, and (ii) modulated by the duration of immersion in a second language environment. This suggests that top–down inhibitory control is most involved at the beginning of immersion. Taken together, the present findings lend support to the psycholinguistic models of bilingual language processing that postulate that top–down active inhibition is involved in language control.

Keywords: executive functions, active inhibition, bilingual language processing, frequency of second language use, Stroop interference

Introduction

In bilingual and multilingual individuals, the ability to switch between languages and maintain conversations in one target language involves cognitive control processes for reducing lexical (Kroll, Bogulski & McClain, 2012; Misra, Guo, Bobb & Kroll, 2012) and grammatical (Kroll, Dussias, Bogulski & Valdes Kroff, 2012; Tokowicz & MacWhinney, 2005) interference between languages. Cognitive control is therefore crucial in order to avoid any negative transfer, the incorrect use of an L1 processing strategy in the L2, which would likely impede the process of understanding (Bjorklund & Harnishfeger, 1995; De Neys & Van Gelder, 2009; MacWhinney,

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2005; Tokowicz & MacWhinney, 2005). Executive functions, especially cognitive inhibition, play an essential role in this control process. Like other psychological constructs, such as memory, executive function is multidimensional. Consequently, several models provide different viewpoints of the basic component processes associated with executive functions (for a review, see Godefroy, Jeannerod, Allain & Le Gall, 2008). Among them, the model of Miyake, Friedman, Emerson, Witzki, Howerter and Wager (2000) postulates a division into the three most discussed executive functions, namely the inhibition of dominant responses ("inhibition"), the shifting of mental sets ("shifting") and the monitoring and updating of information in working memory ("updating"). In this study, we primarily focused on the relation between bilingualism and cognitive inhibition. Different theories of the mind related to cognitive inhibition originated in the 19th century, showing reflex inhibition and central inhibition in the brain. In the wide domain of neuroscience, while various kinds of inhibition can be identified, e.g. lateral inhibition, reciprocal inhibition and recurrent inhibition among others, each kind can be clearly distinguished from another because its mechanism can either be observed neurophysiologically or clearly operationalized in terms of behaviour (Aron, 2007). Unfortunately, this is not the case in psychology. One reason is that cognitive inhibition can only be observed indirectly using experimental paradigms designed to examine many various executive processes. Despite the empirical difficulties to tap these processes, Aron (2007) proposed that there is a major distinction between automatic inhibition (for example, the lateral inhibition between response representations) and active inhibition (the suppression of an irrelevant response). Models of bilingual language processing have postulated that active inhibition occurs in the inhibition of the inappropriate non-target language (Green, 1998). On the basis of this theory, we examined whether the efficiency of active inhibition among bilinguals is influenced by the need to switch language in their daily lives.

Previous studies have shown an improvement of the executive functions based on an increased level of activity in all age ranges. Interestingly, this phenomenon was even observed in age groups that normally exhibit a decreased capacity in their executive functions, i.e. children and older individuals (A. Diamond & Lee, 2011; Zelazo, Craik & Booth, 2004; for a review, see Bialystok, 2007). This observation reinforces the idea that executive functions can be trained by different activities, in particular by those requiring attention, memorization, and control of complex processes (A. Diamond, 2011). Playing the biggest role in the increase of executive function is the use of multiple languages (Bialystok, 2006; Bialystok & DePape, 2009; Costa, Hernández & Sebastián-Gallés, 2008; J. Diamond, 2010; Kroll, Dussias, Bogulski & Valdes Kroff, 2012), as well as playing music (Bialystok & DePape, 2009), playing computer or video games (Bialystok, 2006), or actively performing sports that require high bimanual coordination (A. Diamond & Lee, 2011; for a review, see A. Diamond, 2011). However, taken together, behavioural studies exploring the advantages yielded by bilingualism on executive functions do not provide a clear picture. While several studies reported a clear advantage for performing various tasks involving inhibitory control (e.g. Bialystok, Craik, Klein & Viswanathan, 2004; Bialystok, Craik & Luk, 2008; Costa et al., 2008; Linck, Hoshino & Kroll, 2008), others did not (Carlson & Meltzoff, 2008; Morton & Harper, 2007; for a review, see Costa, Hernández, Costa-Faidella & Sebastián-Gallés, 2009).

Empirical data on the impact of bilingualism on executive functions

A series of studies found that bilingual individuals find it easier to solve conflicts occurring in tasks like the Stroop task (Stroop, 1935), the Simon task (Simon & Ruddell, 1967) or the Tower of Hanoi task. One possible explanation to account for this advantage is that the inhibitory control of bilingual individuals is better trained due to frequent code switching in their daily lives, compared to monolingual individuals (Badzakova-Trajkov, 2008; Bialystok et al., 2004; Bialystok et al., 2008; Costa et al., 2008). In these tasks, a reduced interference effect and/or faster response times are frequently considered to reflect higher capacities of inhibitory control.[1] Some of these behavioural studies on inhibition controlled for biological age (Bialystok et al., 2008; Bialystok, Craik & Ryan, 2006; Gathercole, Thomas, Jones, Guasch, Young & Hughes, 2010) because the efficiency of the executive functions has been shown to vary with age (Best & Miller, 2010; Bjorklund & Harnishfeger, 1995; De Neys & Van Gelder, 2009; A. Diamond, 2006; Treitz, 2006; Zelazo et al., 2004). Using a Stroop task, Badzakova-Trajkov (2008) found reduced Stroop interference for young adult successive[2] bilinguals with different combinations of L1 and L2 (Macedonian–English; German–English), as compared to monolingual young adults (English). Such a bilingual advantage was also observed for older adults (Bialystok et al., 2008) and for children (Gathercole et al., 2010). Furthermore, in young adults, a bilingual advantage was found for the Simon task (Bialystok, 2006; Bialystok & DePape,

[1] Some authors have argued that better monitoring capacities in bilinguals compared to monolinguals are reflected by shorter response times and/or reduced interference effects in an ANT task (Costa et al., 2008), in a flanker task (Costa et al., 2009) or in global–local and trail-making tasks (Bialystok, 2010).

[2] The term successive bilingualism refers to late bilingualism, which means that the L2 has been acquired after the L1, from the age of seven years on (see Meisel, 2007).

2009), an attentional network task (ANT; Costa et al., 2008), a lateralized attention network task (LANT; Tao, Marzecová, Taft, Asanowicz & Wodniecka, 2011), and a flanker task (Luk, de Sa & Bialystok, 2011). A similar bilingual advantage was also reported in older adults with a Simon task (Bialystok et al., 2004; Bialystok et al., 2008; Linck et al., 2008) and in children of different ages with a range of tasks that tested inhibition, e.g. ANT (Yang, Yang & Lust, 2011), the dimensional card sorting task (Bialystok & Martin, 2004; for reviews see Bialystok, 2001, 2005), and ToM tasks (Kovács, 2009). Moreover, a bilingual advantage has also been found in switching tasks (Kovács & Mehler, 2009; Prior & MacWhinney, 2010), which plausibly include both inhibition and shifting processes (Prior & MacWhinney, 2010).

Conversely, several studies failed to show that bilingual older adults had an advantage in inhibitory control in a Stroop task (Kousaie & Phillips, 2012). Furthermore, in children, some studies did not find any advantage resulting from bilingualism, either with a Simon task (Morton & Harper, 2007) or with an ANT task (Carlson & Meltzoff, 2008; for a review, see Costa et al., 2009). To sum up, the above-mentioned behavioural studies examining the effect of bilingualism on executive functions do not unequivocally demonstrate an advantage of bilingualism on executive function. Although there is strong evidence to support the claim that multiple language use favours the training of the executive functions, some studies shed doubt on how general this conclusion is. A factor that may account for the diversity of the results may be the varied relative frequency of language use in the different populations of bilingual individuals. Unfortunately, to date, this linguistic factor has not been systematically taken into consideration. Therefore, our goal was to examine the effects of the frequency of language use on the inhibitory control among highly proficient successive French–German bilinguals.

The present study

The major contribution of the present study was to examine the use of one executive function, inhibitory control in bilingualism, on the performance of an executive task, i.e. the Stroop task. To date there is still no clear-cut picture on the relationship between bilingualism and conflict resolution in executive tasks. Following the hypothesis of A. Diamond and Lee (2011) that all successful programs involved repeated practice and progressively increasing the challenge to the executive functions, we investigated whether the training of task switching in the daily lives of bilingual individuals influenced their performance on the Stroop task. Therefore, in the present study we examined the role of the relative frequency of language use on the inhibitory control. Critically, we investigated the role of the frequency of the daily use of an L2 (German for all participants) on conflict resolution, by testing bilingual participants in two different linguistic environments (either in France, the linguistic environment of their L1, French, or in Germany or Austria, that of the L2, German), while other linguistic factors such as the age of the acquisition (AoA) of the L2 and the proficiency in the L2 were controlled. The rationale was that the regular use of the L2 in the linguistic environment related to this language should increase the activation of the L2. Consequently, we assumed that the L2 has to be inhibited more in the L2 linguistic environment than that of the L1, where this language is not commonly used. Moreover, while successive bilingual individuals in an L1 linguistic environment mostly have to inhibit only one, not highly activated language (i.e. their L2), bilingual individuals living in an L2 linguistic environment often have to inhibit two languages, namely the highly activated automatic L1 (Linck, Kroll & Sunderman, 2009) and the regularly activated/used L2. Therefore, the more frequent the L2 use, the stronger the inhibitory control due to a regular use of L2. Furthermore, as few studies focused on whether the regular use of an additional third language might reinforce the effects of bilingualism (see J. Diamond, 2010; Chertkow, Whitehead, Phillips, Wolfson, Atherton & Bergman, 2010), we decided to include in our study the frequency of use of an L3. In order to study the strength of the inhibitory control, a classic Stroop task was administrated to two groups of proficient successive French (L1) – German (L2) bilingual adults.

Using the Colour Word Stroop task (Stroop, 1935) enabled us to study one particular aspect of executive function, inhibitory control, because, in this task, decisions must be based on task-relevant information in the face of distracting information. Indeed, “two conflicting mental representations are active, each associated with a different response, and attention must be paid to only relevant cues” (Bialystok et al., 2006, p. 1342). Specifically, an ink colour must be identified while ignoring the written word itself. Since word reading is more automatic than colour naming, executive control is required to override the tendency to respond on the basis of the word rather than the ink colour. The need of such control is reflected in slower responses when the word name is competing with the ink colour (i.e. incongruent condition like the word *green* written in red ink) than when it does not (i.e. congruent condition like the word *green* written in green ink). The conflict in the incongruent condition arises because an automatic process (i.e. word reading) disturbs a controlled process (i.e. print colour naming), the former having to be inhibited to allow the latter to take place. The Stroop effect is calculated by subtracting the mean response times in the congruent condition from those in the incongruent condition. Shorter response times (RT) to the incongruent condition, a smaller Stroop effect size, are interpreted to reflect stronger inhibitory control[3] (Badzakova-Trajkov, 2008; Pardo, Pardo, Janer & Raichle, 1990). This definition of the Stroop effect is in line with several preceding studies (Bruchmann, Herper, Konrad, Pantev & Huster, 2010; Coderre, Conklin & Van Heuven, 2011; Liotti, Woldorff, Perez & Mayberg, 2000; Naylor, Stanley & Wicha, 2012; Pardo et al., 1990; Van Veen & Carter, 2005). The "Inhibition effect" was defined as the RT difference between the incongruent and the neutral conditions (Coderre et al., 2011; the notion "Stroop interference" is also employed in the literature to designate this effect: see Badzakova-Trajkov, Barnett, Waldie & Kirk, 2009; Qiu, Luo, Wang, Zhang & Zhang, 2006) and the "Facilitation effect" as the RT difference between the congruent and the neutral condition (Badzakova-Trajkov et al., 2009; Coderre et al., 2011; Hanslmayr, Pastötter, Bäuml, Gruber, Wimber & Klimesch 2008; MacLeod & MacDonald, 2000). Thus, the Stroop effect (incongruent–congruent) could be divided into an Inhibition effect (incongruent–neutral) and a Facilitation effect (neutral–congruent).

We expected to replicate the well-known bilingual advantage in the performance of an experimental task involving executive function, i.e. the Stroop task. This effect can be predicted on the basis of both the INHIBITORY CONTROL (IC) model (Green, 1998) and the BILINGUAL INTERACTIVE ACTIVATION+ (BIA+) model (Dijkstra & Van Heuven, 2002; Van Heuven, Dijkstra & Grainger, 1998) in case of conflict resolution. Critically, with respect to the central question of the present study, i.e. the role of the frequency of language use on inhibitory control, we predicted that the size of the Stroop effect should vary as a function of the L2 use frequency, as indicated by the linguistic environment (either L1, France, or L2, Germany). This means that the higher the frequency of the L2 use, the smaller the size of the Stroop effect (better inhibitory control). Moreover, we predicted that Language (L1 vs. L2) has an impact on the degree of interference in the Stroop task. The Stroop effect is predicted to be larger in the L1 than in the L2 due to the higher automaticity and activation of the L1. However, this difference should decrease when the frequency of L2 use increases, as in this environment the L2 becomes more automatic. Thus, we predicted an interaction between frequency of L2 use (e.g. linguistic environment) and Language for the Stroop effect, such that the more the L2 is used, the more automatic it has become, and thus the larger the Stroop effect will be in the L2. We simultaneously predicted a smaller Stroop effect for the L1 in the L2 environment, due to decreased activation of the L1.

Method

Participants

Sixty-five right-handed (Edinburgh Handedness Inventory) participants were recruited. Among them, 34 were successive French (L1) – German (L2) bilinguals living either in France ($n = 17$) or in Germany ($n = 17$), and 31 were French monolingual individuals. One bilingual participant was excluded due to missing data for a multiple regression analysis. By their own account, the participants had no history of current or past neurological or psychiatric illnesses; they had normal or corrected-to-normal vision and normal colour vision. They were paid 10€ per hour for their time. Table 1 displays several linguistic and non-linguistic aspects asked in a questionnaire before the start of the experiment.

Bilingual participants

Sixteen successive French (L1) – German (L2) bilinguals (12 female) of an average age of 26.8 ± 3.7 years were tested in their L1 environment (Paris, France) and seventeen successive French (L1) – German (L2) bilinguals (15 female) of an average age of 32.4 ± 5.2 years were tested in their L2 environment (Hamburg, Germany, or Vienna, Austria). They were all late learners of their L2, German, which they had started to study by the age of 10 at secondary school in France. The mean AoA of German as their L2 was 11.0 ± 1.2 years. A criterion for accepting participants for the study was their regular exposure to German during the past three years and at present. Twenty-six out of 33 bilinguals (79%) reported using an additional L3 whereas only seven out of 33 bilinguals (21%) reported using an additional L4 on a daily basis.

Each bilingual participant was asked to assess their own proficiency in German on a five-point scale from EXCELLENT PROFICIENCY (1) to POOR PROFICIENCY (5) in the categories COMPREHENSION, PRODUCTION, READING and WRITING. Furthermore, proficiency in German was evaluated with two standardized tests on their proficiency in German as a foreign language, including the DAF test (Das Zertifikat, DAF – Deutsch als Fremdsprache, Einstufungs- und Diagnostiktest). Their evaluated proficiency and objective scores are presented in Table 1. The two groups of bilinguals (L1 environment, L2 environment) differed on the following background measures: Bilinguals in the L2 environment were on average older (32.4 ± 5.2 years) than bilinguals in the L1 environment (26.8 ± 3.7 years; $p < .001$). They also reported a higher frequency of L2 use (53.6 ± 14.7% vs. 28.7 ± 17.8%; $p < .001$), a longer duration of

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[3] Alternative explanations of control processes involved in the performance of a Stroop task have been proposed; for example, Blais and Bunge (2010) stress that control is exerted on a local stimulus-level control, and Bugg (2012) claims that multiple levels of cognitive control are implicated in the control processes in a Stroop task.

Table 1. *Results from the evaluation of the participants on their language background and on activities such as practising music, doing sports that require high bimanual coordination, and playing computer/video games. Means and standard deviations (SDs) are indicated for each category.*

	Bilinguals – L1 environment ($n = 16$)		Bilinguals – L2 environment ($n = 17$)		Monolinguals ($n = 31$)	
	Mean	SD	Mean	SD	Mean	SD
Age (years)[1]	26.8	3.7	32.4	5.2	25.2	4.1
Frequency of L2 use (%)[2]	28.7	17.8	53.6	14.7	0.4	0.8
Frequency of L3 use (%)[3]	3.4	5.8	3.5	6.1	0.0	0.1
Frequency of L4 use (%)	0.8	2.2	0.8	1.7	0.0	0.0
L2 PA (1 = best, 5 = poor)	1.7	0.5	1.4	0.5	—	—
L2 PT (%)	85.9	9.3	87.3	8.4	—	—
Immersion in L2 environment (years)[4]	1.9	1.7	8.2	4.6	—	—
Age of immersion (years)[5]	19.1	3.7	23.8	3.5	—	—
Music practice (hr/week)	0.6	1.3	0.9	1.6	0.4	0.7
Sport practice (hr/week)[6]	2.7	2.2	3.8	3.8	1.7	2.1
Video/Computer games (hr/week)	0.4	0.9	0.4	0.8	0.9	1.5

L2 PA = Proficiency in German – Autoevaluation; L2 PT = Proficiency in German – Test (DAF – Deutsch als Fremdsprache); * $p < .05$, ** $p < .01$, *** $p < .001$

[1] Bilinguals–L2 vs. Bilinguals–L1***, Bilinguals–L2 vs. Monolinguals***.

[2] All the three pairwise comparisons***.

[3] Bilinguals–L2 vs. Monolinguals**, Bilinguals–L1 vs. Monolinguals*.

[4] Bilinguals–L1 vs. Bilinguals–L2***, Bilinguals–L2 vs. Monolinguals***, Bilinguals–L1 vs. Monolinguals*.

[5] Bilinguals–L1 vs. Bilingual–L2***.

[6] Bilingual–L2 vs. Monolinguals*.

immersion in an L2 environment (8.2 ± 4.6 years vs. 1.9 ± 1.7 years; $p < .001$), and a higher age of immersion in an L2 environment (23.8 ± 3.5 years vs. 19.1 ± 1.7 years; $p < .001$).

Monolingual participants

Thirty-one native French speakers (22 females) with an average age of 25.2 ± 4.1 years who had had little use of a foreign language during the past three years and at present (see Table 1) were selected.

As shown in previous studies, additional factors such as socio-economic status (Gathercole et al., 2010; Morton & Harper, 2007), musical practice (Bialystok & DePape, 2009), video/computer game playing (Bialystok, 2006) or physical activity requiring high coordination (A. Diamond & Lee, 2011) may influence the performance in a task on inhibitory control. Therefore, these factors were controlled for in the present study and participants of the two language groups did not differ significantly on either of these factors (Table 1).

Stimuli

An adapted version of the original Stroop task (Stroop, 1935) was used in the experiments. The task was a manual colour response task in which the participants were asked to identify the print colour of the stimuli. Depending on the condition, stimuli were colour words (e.g. “red”, “blue”, etc.) or non-colour words (e.g. “cat”, “dog”, etc.). All stimulus words were monomorphemic, monosyllabic words. The three different conditions were congruent, incongruent and neutral. In the congruent condition the meaning of the colour word and the print colour matched, in the incongruent condition the meaning of the colour word and the print colour differed and in the neutral condition, non-colour words were presented in equally varying print colours as in the congruent and incongruent conditions. In L1, French, the following four colour words were presented: ROUGE “red”, BLEU “blue”, JAUNE “yellow”, VERT “green” and in the L2, German, the four corresponding colour words were used: ROT “red”, BLAU “blue”, GELB “yellow”, GRÜN “green”. In the neutral condition, four non-colour words were presented in the same four print colours. This control condition was considered as neutral because stimuli did not include colour information, the critical semantic information causing an interference in a Colour Word Stroop task (for a similar use of the neutral condition, see Badzakova-Trajkov et al., 2009; Hanslmayr et al., 2008; MacLeod & MacDonald, 2000; Qiu et al., 2006). Initial letters

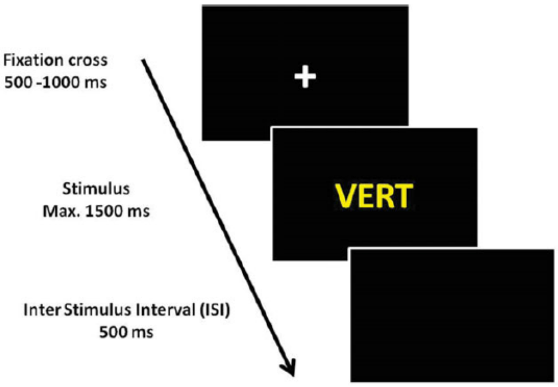

Figure 1. (Colour online) The timing of a trial in the manual version of a Stroop task is displayed.

of colour (congruent and incongruent conditions) and non-colour words (neutral condition) did not share initial letters. CHAT “cat”, CHIEN “dog”, MAIN “hand”, PIED “foot” were chosen as neutral words in L1, French, and their translation equivalents in L2 (German): KATZE “cat”, HUND “dog”, HAND “hand”, FUSS “foot”. The stimulus words, written in capitals, in “Calibri” font and in font size 48, were presented individually against a black background in the centre of the screen.

Procedure

Some aspects of the stimulus presentation and the experimental procedure were taken from Bruchmann et al. (2010). The stimulus presentation design was created with the program *E-Prime 2.0* (Psychological Software Tools, Pittsburgh, PA). Each stimulus word was preceded by a fixation cross in the centre of the screen (Figure 1). The duration of the fixation cross varied between 500 ms and 1000 ms (500, 625, 750, 875, 1000 ms equally distributed and pseudo-randomized among the stimuli) in order to avoid systematic expectancy to be built up by the participants. The fixation cross was immediately followed by the stimulus, which was presented until one of the four colour response keys was pressed or maximally for 1500 ms if no key was pressed. The inter-stimulus interval (ISI) was 500 ms. Response time (RT) was defined as the interval between the stimulus onset and pressing a response key.

Participants were seated in front of a laptop (Dell, 14″ screen) in a common writing position with both hands positioned on the keyboard. The room contained good lighting conditions. Written instructions were given to the subjects and repeated before running the experiment. The participants were asked to indicate as fast and as correctly as possible the print colour of the stimulus word by pressing one of the four response buttons. The colours were also indicated on the lower part of the screen to facilitate the colour-key-assignment. The keys D, F, J and K were chosen in order to allow the usual position of the hands on the keyboard. The keys had to be pressed with the index and middle fingers of the left and the right hand. The colour-finger-assignment was counterbalanced between the subjects so as to vary the fingers and the hand used for each colour but kept constant during the experiment for every single participant.

In order to allow the participants to learn the colour–key correspondences, two practice blocks of 40 trials each were presented before the six experimental blocks. For the bilinguals, a block with words in French was presented first, followed by a second block with words in German. For the monolinguals, both practice blocks consisted of words in French. Feedback on the percentage of correct answers was given after each practice and experimental block. If the accuracy was at least 80% after the second practice block, the experiment was started; if not, the two practice blocks were repeated.

The participants were tested in six blocks each containing 72 trials. In each block, there were 24 congruent stimuli, 24 incongruent stimuli and 24 neutral stimuli, presented in a pseudo-randomized order. A number of constraints were used for the pseudo-randomization. First, no more than three words of the same experimental condition were presented in succession. Secondly, no word and no print colour were repeated immediately. Third, the first stimulus of each block was a neutral one. The pseudo-randomized order of trials was created using the program *Conan* (Nowagk, 1998). Moreover, for each bilingual participant a list was created in which the presentation order of the six blocks (three French and three German) was counterbalanced using the following constraint: No more than two blocks of one language were presented in succession. Monolingual participants saw six blocks in French, but only three of them were used for further analyses in order to match the number of blocks presented to the bilinguals in their L1. The three chosen L1 blocks were those corresponding to the distribution of the L1 block positions for the bilinguals. The participants could take a short pause between the blocks and continue when ready by pressing the spacebar. The experiment lasted about 25 minutes.

Before starting the experiment with the bilingual participants, a conversation in German was held for about 15 minutes between each participant and the experimenter, a German native speaker (the first author of the present study) in order to activate the second language of the participants. Moreover, a language history questionnaire had to be completed. The questionnaire was in German for the bilingual participants, in French for the monolingual participants. Both, the conversations and the questionnaire in German were intended to activate the L2 processing by switching the language processing mode to

German (see Isel, Baumgaertner, Thrän, Meisel & Büchel, 2010).

Data analysis

Response time (RT) was defined as the interval between the onset of the stimulus word and the manual response on the keyboard. Time-out was set at 200 ms and at 1500 ms; if the participant responded before 200 ms or after 1500 ms, the response was coded as missing. We averaged the RTs for correct responses in the nine experimental conditions across participants and across items. We excluded RTs ± two standard deviations from each participant's mean in each experimental condition from the statistical analysis. The average percentage of outliers for bilinguals was 4.44 ± 1.03% in L1 and 4.62 ± 1.19% in L2, and for monolinguals 4.44 ± 0.98%.

We subjected the results of errors and response times to a three-way analysis of variance (ANOVA) in which Condition (C; three levels: congruent, incongruent, neutral) and Language (L; two levels: French, German) were considered as within-subjects factors, and Linguistic environment (E; two levels: bilingual in the L2 linguistic environment, bilingual in the L1 linguistic environment) as a between-subjects factor.

Then, to ensure that we were able to replicate the bilingualism advantage with a Stroop task, a two-way ANOVA in which Condition was considered as a within-subjects factor and Group (G; two levels: bilingual, monolingual) as a between-subjects factor (C3 × G2) was run on errors and RT. To test the effect of Language in the bilingual group, an additional two-way ANOVA in which Condition and Language were considered as within-subjects factors (C3 × L2) was calculated. For each ANOVA, Greenhouse-Geisser correction was applied where necessary for sphericity assumption violations and Bonferroni correction was used for post hoc tests.

Finally, two multiple regression analyses were conducted on RT in order to test the role of the frequency of foreign language use and other linguistic factors on the Stroop effect size, which constitutes the central question of the present study.

Five between-subject factors were included to analyse their respective part of variance on the Stroop effect (incongruent–congruent) in L1 and L2: the frequency of L2 use, of L3 use, the L2 proficiency, duration of immersion in an L2 environment, and age of immersion. Frequency of L3 use was considered to be a relevant predictor because 26 out of 33 bilinguals (79%) reported using an additional L3. In contrast, only 7 out of 33 bilinguals (21%) reported using an additional L4 on a daily basis. Thus, frequency of L4 use was not included as a predictor in the multiple regression analysis. A significance level of .05 was used for all statistical tests.

Results

Analyses of errors

As neither the main effect Linguistic environment (E; $p > .10$) nor the interaction between Linguistic environment and Condition and Language were significant ($F < 1$), data of the two groups of linguistic environments were collapsed for further analyses. For bilinguals, the averaged percentage of errors was 2.40 ± 2.23% in L1 and 2.10 ± 2.05% in L2, and for monolinguals 3.27 ± 3.11%.

Condition by Language Group interaction (C3 × G2)

Error rates are displayed for L1 in Table 2. Repeated measures ANOVA (C3 × G2) with Condition (three levels: congruent, incongruent, neutral) as a within-subjects factor and Language Group (two levels: bilingual, monolingual) as a between-subjects factor showed a main effect of Condition ($F1(2,124) = 4.812$, MSE = 4.69, $p < .05$). This effect was due to significantly increased error rates in the incongruent condition (3.45 ± 3.65%) compared to the congruent condition (2.33 ± 2.81%; $F1(1,62) = 10.10$, MSE = 8.24, $p < .01$). There was no main effect of Language Group ($p > .10$) and no significant Condition by Language Group interaction ($p > .10$).

Condition by Language interaction (C3 × L2)

Error rates for bilinguals are displayed in Table 3. The ANOVA failed to show either a main effect of Condition ($p > .10$), a main effect of Language ($p > .10$) or a Condition × Language interaction ($F < 1$).

Analyses of RT

As neither the main effect Linguistic environment (E) nor the interaction between Linguistic environment and Condition and Language were significant (Fs < 1), data of the two groups of linguistic environments were collapsed for further analyses.

Condition by Language Group interaction (C3 × G2)

Response time data is displayed for L1 in Table 2 and Figure 2. The ANOVA showed a significant main effect of Condition ($F1(2,124) = 96.43$, MSE = 592.3, $p < .001$). This effect reflects that averaged response times were longer in the incongruent condition (678.3 ± 97.9 ms) than in the (i) congruent condition (625.9 ± 91.7 ms; Stroop effect = 52.4 ms; $F1(1,62) = 151.91$, MSE = 1168.15, $p < .001$) – mirroring the increased error rates in the incongruent condition (see

Table 2. *Error rates (ERR; %) and response times (RTs; ms) in the three experimental conditions (congruent, incongruent and neutral) with the standard deviations (SDs, in parentheses) for the two language groups (bilinguals, monolinguals) in L1 blocks of the Stroop task.*

		Bilinguals ($n = 33$)	Monolinguals ($n = 31$)	Total
	Condition	Mean (SD)	Mean (SD)	Mean (SD)
ERR	Congruent	2.06 (2.57)	2.61 (3.05)	2.33 (2.81)
	Incongruent	2.70 (2.84)	4.26 (4.25)	3.45 (3.65)
	Neutral	2.45 (3.19)	2.94 (3.11)	2.69 (3.14)
RT	Congruent	632.5 (76.2)	618.9 (106.5)	625.9 (91.7)
	Incongruent	675.7 (81.5)	681.0 (114.2)	678.3 (97.9)
	Neutral	652.2 (75.0)	638.8 (105.4)	645.7 (90.5)

Table 3. *Error rates (ERR; %) and response times (RTs; ms) for L1 and L2 of bilinguals in the three experimental conditions (congruent, incongruent and neutral) with the standard deviations (SDs, in parentheses) for bilinguals in L1 and in L2 blocks of the Stroop task.*

		L1 French	L2 German	Total
	Condition	Mean (SD)	Mean (SD)	Mean (SD)
ERR	Congruent	2.06 (2.57)	1.67 (2.26)	1.86 (2.14)
	Incongruent	2.70 (2.84)	2.64 (2.61)	2.67 (2.34)
	Neutral	2.45 (3.19)	2.00 (2.68)	2.23 (2.69)
RT	Congruent	632.5 (76.2)	630.3 (80.3)	630.9 (77.9)
	Incongruent	675.7 (81.5)	660.2 (82.3)	664.1 (80.9)
	Neutral	652.2 (75.0)	641.3 (76.6)	644.1 (75.1)

section 3.1.1.) – and (ii) neutral condition (645.7 ± 90.5 ms; Inhibition effect = 32.7 ms; $F1(1,62) = 58.11$, MSE = 1189.90, $p < .001$). Moreover, further post-hoc tests showed that averaged response times were shorter in the congruent condition (625.9 ± 91.7 ms) compared to the neutral condition (645.7 ± 90.5 ms; Facilitation effect = 19.8 ms; $F1(1,62) = 54.59$, MSE = 459.05, $p < .001$). Further analyses indicated that the size of the Inhibition effect (incongruent–neutral) did significantly differ from the size of the Facilitation effect ($F1(1,62) = 5.202$, MSE = 1074.53, $p < .05$). In contrast, the main effect of Language Group was not significant ($F < 1$). Moreover, the ANOVA revealed a significant Condition by Language Group interaction ($F1(2,124) = 3.99$, MSE = 592.3, $p < .05$, $\eta^2 = .02$), indicating that the effect size between conditions did vary across the two groups of participants (Figure 3). Post-hoc comparisons on the Stroop effect (incongruent–congruent) showed that this interaction was due to a larger Stroop effect in monolingual participants (62.1 ms) than among bilingual participants (43.3 ms; $F1(1,62) = 4.85$, MSE = 1168.15, $p < .05$, $\eta^2 = .04$). The Inhibition effect (incongruent–neutral) mirrored the Stroop effect (incongruent–congruent), as it was significantly larger for the monolingual participants (42.2 ms) than for the bilingual participants (23.6 ms; $F1(1,62) = 4.68$, MSE = 1189.90, $p < .05$, $\eta^2 = .04$). In contrast, the size of the Facilitation effect (neutral–congruent) did not differ significantly between the two groups ($F < 1$). In order to examine whether the differences in Stroop and Inhibition effect size between the two language groups are mainly due to RT differences in one of the experimental conditions (congruent, incongruent, neutral), independent samples *t*-tests were done on the RTs in each experimental condition. RTs did not differ between language groups either in the congruent, the incongruent, or the neutral conditions ($ts < 1$). This result suggests that group differences in Stroop and Inhibition effects cannot simply be attributed to RT differences in only one of the three experimental conditions (neutral, congruent, incongruent).

Condition by Language interaction (C3 × L2)

Response time data for the bilinguals' L1 and L2 are displayed in Table 3 and Figure 4. The Stroop effect (incongruent–congruent) was predicted to be larger in the L1 than in the L2 due to the higher automaticity

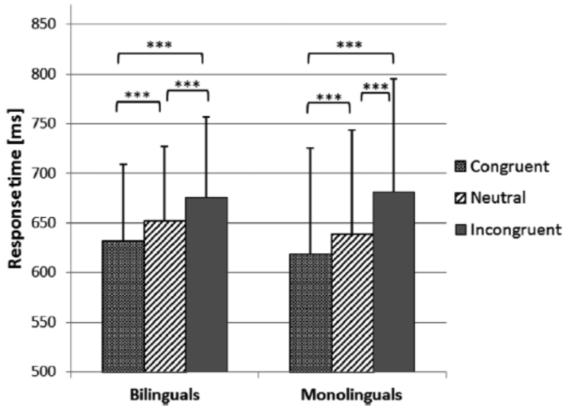

Figure 2. Mean response times (ms) and the standard deviations in the congruent, neutral and incongruent experimental conditions are displayed for bilinguals and for monolinguals in their L1.

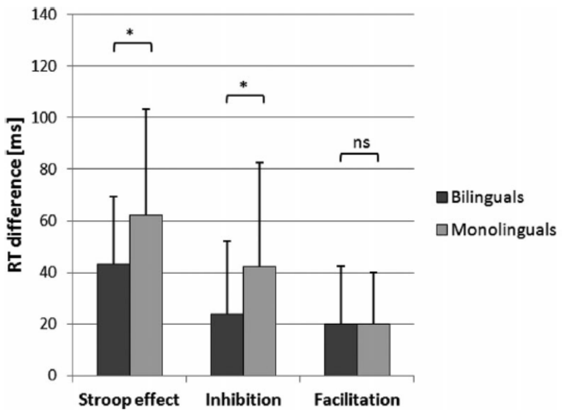

Figure 3. Mean Stroop Effect (ms) (RT$_{\text{incongruent}}$ – RT$_{\text{congruent}}$; Response time difference between the incongruent and the congruent condition), Inhibition effect (RT$_{\text{incongruent}}$ – RT$_{\text{neutral}}$) and Facilitation effect (RT$_{\text{neutral}}$ – RT$_{\text{congruent}}$) with their respective standard deviations are given for bilinguals and monolinguals in their L1.

and activation of L1. A two-way repeated measures ANOVA (C3 × L2) with Condition (3 levels: congruent, incongruent, neutral) and Language (2 levels: French, German) as within-subjects factors showed a significant main effect of Condition ($F1(2,64) = 54.90$, MSE = 405.33, $p < .001$) but not of Language ($p > .05$). However, there was a significant Condition × Language interaction ($F1(2,64) = 4.46$, MSE = 171.19, $p < .05$). This interaction effect indicates that the Stroop effect (incongruent–congruent) was significantly larger in the L1 (43.3 ms) compared to the L2 (29.9 ms; $F1(1,32) = 9.06$, MSE = 327.4, $p < .01$; Figure 5). This can be interpreted in terms of higher automaticity/activation of the first language.

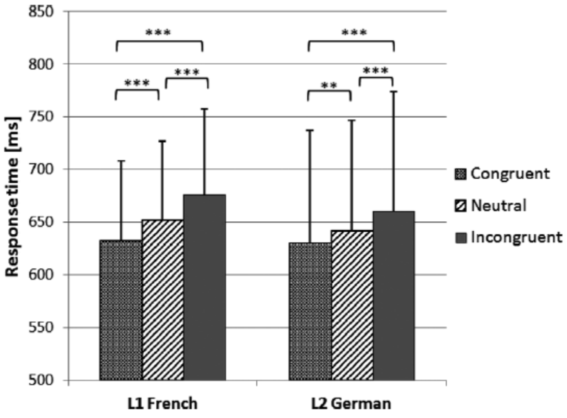

Figure 4. Mean response times (ms) and the standard deviations in the congruent, neutral and incongruent experimental conditions are plotted for bilinguals in their L1 and L2.

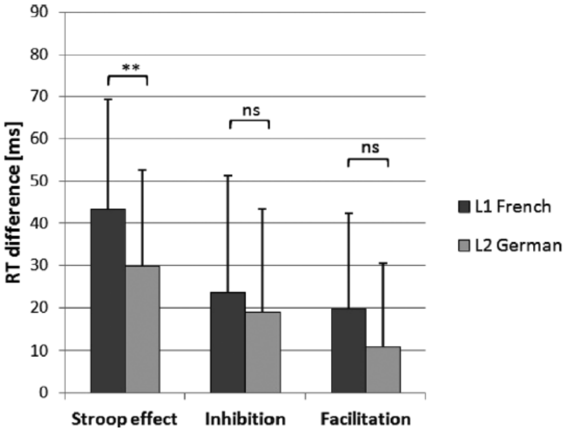

Figure 5. Mean Stroop Effect (ms) (RT$_{\text{incongruent}}$ – RT$_{\text{congruent}}$; Response time difference between the incongruent and the congruent condition), Inhibition effect (RT$_{\text{incongruent}}$ – RT$_{\text{neutral}}$) and Facilitation effect (RT$_{\text{neutral}}$ – RT$_{\text{congruent}}$) with their respective standard deviations are indicated for L1 and L2 of bilinguals.

The impact of different linguistic factors on the Stroop and Inhibition effects in L1 (French)

A multiple regression analysis was conducted in order to determine which among the five linguistic factors we selected (i.e. frequency of L2 use, frequency of L3 use, L2 proficiency, duration of immersion in the L2 environment, and age of immersion) best account for the variance of the size of the Stroop effect (incongruent–congruent) in the L1 of the bilinguals. The results of the regression analysis indicated that the five predictors explained 27.1% of the variance of the Stroop effect size (Adjusted $R^2 = .271$, $F(5,32) = 3.377$, $p < .05$, Cohen's $f^2 = .37$; see Table 4). The Cohen's f^2 of .37 indicates that this effect is in fact quite large. It was found that two variables significantly

Table 4. *Multiple regression analysis of L1 Stroop effect ($RT_{incongruent} - RT_{congruent}$) size in bilinguals with frequency of L2 use, frequency of L3 use, L2 proficiency, duration of immersion in an L2 environment and age of immersion as predictor variables.*

Predictors	R^2 increments (Coefficient β)	t	p
Constant	103.583	2.255	.032
Frequency of L2 use (%)	−.171	−0.922	.365
Frequency of L3 use (%)	−.371	−2.147	.041
L2 proficiency (%)	−.282	−1.696	.101
Duration of immersion (years)	.587	3.325	.003
Age of immersion (years)	.080	0.464	.647

Table 5. *Multiple regression analysis of L2 Stroop effect ($RT_{incongruent} - RT_{congruent}$) size with frequency of L2 use, frequency of L3 use, L2 proficiency, duration of immersion in an L2 environment and age of immersion as predictor variables.*

Predictors	R^2 increments (Coefficient β)	t	p
Constant	−12.867	−0.319	.752
Frequency of L2 use (%)	−.234	−1.258	.219
Frequency of L3 use (%)	.083	0.481	.634
L2 proficiency (%)	.122	0.732	.470
Duration of immersion (years)	.631	3.566	.001
Age of immersion (years)	.079	0.459	.650

predicted the L1 Stroop effect size: the frequency of L3 use was negatively related to L1 Stroop effect size ($\beta = -.371, p < .05$), while the duration of the immersion in the L2 environment was positively related to L1 Stroop effect size ($\beta = .587, p < .01$). In contrast, for the L1 Inhibition effect (incongruent minus neutral), the model of multiple regression using the same predictors found none of the factors to be significant ($F < 1$).

The impact of different linguistic factors on the Stroop and Inhibition effects in L2 (German)

A multiple regression analysis was also conducted in order to predict the size of the L2 Stroop effect (incongruent–congruent) from the following factors: frequency of L2 use, frequency of L3 use, L2 proficiency, duration of immersion in an L2 environment, and age of immersion. The results of the regression indicated that the five predictors explained 26.5% of the variance of Stroop effect size (Adjusted $R^2 = .265$, $F(5,32) = 3.311$, $p < .05$, Cohen's $f^2 = .36$). The Cohen's f^2 of .36 indicates that this effect is also quite large. The duration of immersion in the L2 context was found to be positively related to the L2 Stroop effect size ($\beta = .631$, $p < .001$; Table 5). In contrast, for the L2 Inhibition effect (incongruent minus neutral), the model of multiple regression using the same predictors found none of the factors to be significant ($F < 1$).

Discussion

Bilingual advantage on inhibitory control

In the present study, we examined the extent to which second language use impacts cognitive control. Our starting point was the hypothesis that the frequency of the L2 language use in successive bilingual individuals has an effect on their inhibitory control. To study the factor frequency of L2 use, we tested bilingual participants from two linguistic environments. Cognitive control was studied while successive French–German bilinguals living either in French or German linguistic environments performed a Stroop task on both French and German words. Moreover, an additional control group constituted of monolingual native French speakers who lived in France was tested. Our results provide a clear-cut picture: the current immersion in a second language environment, i.e. an environment with high frequency of L2 use, is not a sufficient condition for improving the efficiency of the inhibition mechanism, as our ANOVA failed to show a modulation neither of the Stroop effect (incongruent–congruent) nor of the Inhibition effect (incongruent–neutral) as a function of the linguistic environment. Multiple regression analyses indicated that the use of multiple languages did play a central role for training inhibition, not, contrary to our expectations, by the frequency of the L2 use, but surprisingly, by the frequency of the L3 use, instead. In addition, the duration of immersion in an L2 environment was also a determining factor for explaining the efficiency of the inhibitory control, as it was found to be positively related to the L2 Stroop effect size.

The frequency of the L3 language use was negatively correlated to the L1 Stroop effect (incongruent–congruent) size. The more the bilinguals used an additional third language, the smaller their Stroop effect was. This result indicates that bilinguals who are highly trained to control a third language on a daily basis are less disturbed by interferences between reading and colour naming in the incongruent condition of a Stroop task. This finding suggests that the frequency of daily language use might be a determining factor to account for the better capacities of bilingual individuals to inhibit inappropriate/distracting information in tasks involving the resolution of conflicts. Our data reinforce the idea proposed by J. Diamond

(2010) that additional language use beyond bilingualism might even increase a benefit on executive functions. Nevertheless, an alternative interpretation might be that additional language use of an L3 further decreases the respective language activation due to the reduction of the frequency of use of each language (Gollan, Montoya, Fennema-Notestine & Morris, 2005); consequently the Stroop effect could decrease due to reduced interference.

However, given the absence of correlations between L1 and L3 ($p > .10$) as well as between L2 and L3 ($p > .10$) frequency of use, we can reasonably reject an interpretation in terms of decrease of language activation. Rather, our data suggest that the relation between L3 frequency of use and L1 Stroop effect size that we report here might be better explained in terms of an enhancement of inhibitory control due to the regular use of several languages.

Moreover, the observation in the present study that the duration of the immersion positively correlated with the Stroop effect in both languages constitutes an argument in favour of a model postulating increased inhibitory control rather than decreased language activation. It is likely that at the beginning of the immersion in an L2 environment, there is a huge challenge to control the language use as the control over languages is plausibly not yet automatized, and, therefore might require strong top–down inhibitory control. As the duration of immersion increases, the control processes may at least partially become automatized and top–down control gets less implicated. For this reason, in our study, maximal bilingual advantage was found in the case of short rather than long durations of immersion. Nevertheless, although the Stroop effect varies as a function of the duration of the immersion, it remains smaller than it does for monolinguals.

In addition to the positive correlation between the Stroop effect size and the duration of the immersion observed for both languages of the bilinguals (L1 and L2) the Stroop effects in the two languages were positively correlated ($\beta = .460$, $p < .01$). On the basis of this observation, the following rationale for attempting to separate between an inhibition and an activation account explaining the bilingual advantage is proposed: Language activation is supposed to vary with respect to language dominance, which is to a large degree dependent on the frequency of the use of each language as well as on the duration of the immersion in the respective language environment. If the Stroop effect size mainly depends on the language activation, the correlation between the Stroop effects in the two languages should be negative: increased activation of one language due to its frequent use should be accompanied with a reduced activation of the other language. In the present study, we found the reverse result (positive correlation) suggesting that bilingualism advantage could be explained by the differences in the inhibitory control.

Moreover, we were able to replicate the advantage of bilingualism both for the Stroop effect (incongruent–congruent) and for the Inhibition effect (incongruent–neutral) as already found in previous studies (Badzakova-Trajkov, 2008; Bialystok, 2006; Bialystok & DePape, 2009; Costa et al., 2008). This reinforces the idea that activities such as multiple language use are most likely to cause an improvement of the executive functions, even if young adults already have a high capacity (A. Diamond, 2006, 2011). Overall, the bilingual participants performed the Stroop task better than the monolingual individuals. This was mainly due to the fact that bilinguals were less disturbed in the incongruent condition in comparison with the monolinguals as indicated by the significantly smaller Inhibition effect for the bilinguals (i.e. 23.6 ms) than for the monolinguals (i.e. 42.2 ms). Taken together, these results converge to show that in comparison with monolinguals bilinguals have better inhibitory control as they are more efficient in order to suppress distracting information when this information competes with the information needed to perform a cognitive task.

The absence of variation of the size of the Stroop effect in the course of the experiment suggests that the Stroop effect size does not depend on short-term practice of a Stroop task. In contrast, given the advantageous effect of bilingualism the Stroop effect size appears to be modulated by long-term training.

Effect of Language on the Stroop effect

A further hypothesis tested in the present study was that the interference of the automatic process of reading on the (more) controlled process of print colour naming should be stronger in L1 than in L2 due to the higher automaticity of L1 compared to L2. Therefore, we predicted a larger Stroop effect (incongruent–congruent) in L1 than in L2. Our data confirmed this prediction: A larger Stroop effect was found in the L1 as opposed to the L2. This finding can be interpreted within the framework of the temporal delay assumption, as derived from the BIA+ model (Dijkstra & Van Heuven, 2002), i.e. that the access to phonological and semantic codes is assumed to be delayed in the L2 in comparison to the L1. Under this assumption, the L2 takes more time to be activated than the L1 in bilinguals. Due to slower lexical access in the L2, L2 words should interfere less in the Stroop task. Interestingly, the L1 remained the dominant language in the bilingual individuals we tested in the German linguistic environment as suggested by the larger effect in the L1 than in the L2. Note, however, that a change of language dominance has been shown to occur after a longer stay in the L2 environment. Indeed, Bahrick, Hall, Goggin, Bahrick and Berger (1994), using different grammatical and vocabulary tests, found a change of dominance in favour of L2 for a stay in the L2 environment around 12 years. Attrition of L1, that is language loss, can be one of the consequences of longer stays in an L2 environment (Köpke, 2004, for a review; Schmid & Köpke, 2007).

Models on bilingual language processing

In the present section, we will attempt to discuss which of the two models of bilingual language processing (i.e. Inhibitory Control and Bilingual Interactive Activation models) can better account for the empirical data we have presented here.

The INHIBITORY CONTROL (IC) model (Green, 1998) postulates a higher-order level of attentional control being exerted both on linguistic and non-linguistic domains. In the IC model, this higher-order level of control is called the Supervisory Attentional System (SAS). The SAS is assumed to regulate the activation of lexical and phonological units. The justification of such a top–down inhibitory control in language selection relies on the assumption that first and second languages (and further languages for multilingual individuals) are initially co-activated (Brysbaert, 2003; Dijkstra, 2005). Consequently, this language co-activation requires top–down inhibitory control in order to avoid inter-lingual interferences. The language control process is executed via multiple levels of control. Activation of each language is regulated via language TAGS by their respective “language task schemas”, which are themselves controlled by the SAS. If the assumption that the SAS constitutes a general inhibitory control exerted on language selection in a multilingual environment is valid, then multiple language use may function as training to this control mechanism. Bilinguals may thus have an advantage over monolinguals in top–down inhibitory control. Furthermore, inhibitory control is expected to be more efficient in suppressing a less dominant language than a more dominant language in bilingual language use.

An alternative psycholinguistic model on bilingual language control is the BILINGUAL INTERACTIVE ACTIVATION+ (BIA+) model (Dijkstra & Van Heuven, 2002; Van Heuven et al., 1998). Like the IC model (Green, 1998), the BIA+ model postulates an initial co-activation of both languages in bilingual individuals. In the BIA+ model, all levels of inhibitory control on language selection and inhibition are specific to the language domain. Words of the non-target language are inhibited by so-called “language nodes”. Therefore, a crucial difference between the IC model and the BIA+ model lies in the localisation of the levels of control on language selection and inhibition. Whereas the IC model relies on the assumption of an active top–down inhibition, the BIA+ postulates an automatic inhibition, i.e. a lateral inhibition between language nodes. In this mechanism, as one language node accumulates more evidence, the node inhibits the lexical representations associated with the other language nodes; until, finally, the winner takes all. Thus, language selection in the BIA+ mainly relies on differences between activation levels of L1 and L2. Dijkstra and Van Heuven (2002) point out that, in bilingual language use, the L2 is generally activated to a lower level than the L1 (see temporal delay assumption). The difference in resting activation of the L1 and L2 is supposed to be due to differences in frequency of use as well as to language dominance.[4] Finally, following the assumption of a higher-order level of control being exerted both on linguistic and non-linguistic domains, the IC model can account for bilingual advantages either in tasks involving a linguistic component (e.g. Stroop task) or not (e.g. Simon task); in contrast, the BIA+ can only account for advantages in tasks involving a linguistic component.

Akin to the assumption of a temporal delay of lexical access in L2 for bilinguals made in the BIA+ model, Gollan et al. (2005) proposed that each of a bilingual’s languages, including even their L1, is less activated at rest, and thus has weaker links to the conceptual level, than in monolingual language use. Likewise, Ivanova and Costa (2008) and Pyers, Gollan and Emmorey (2009) claimed that bilinguals’ disadvantages in lexical access in their L1 compared to monolinguals may be due to the reduced frequency of use devoted to each single language. Deducing from these hypotheses on frequency-dependent differences, a potential advantage of bilingualism in a task requiring the inhibition of linguistic information – like the Stroop task – may primarily be caused by the lower activation of each of the bilinguals’ languages. Top–down inhibition may therefore be more efficient on the lower activated L1 in bilinguals in comparison to monolinguals.

In our study, the observation of a bilingual advantage for performing tasks involving inhibitory control could be explained either by an inhibition theory (i.e. inhibit interference of the automatic process of reading on the more controlled process of colour naming) or by an activation theory (i.e. lower activation level of the L1 that would explain the reduced interference of reading on naming). However, given the assumption that bilingual or multilingual language use involves inhibition of the non-target language(s), the observation that the size of the Stroop effect in bilinguals was modulated by the frequency of the use of a foreign language, here the L3 not the hypothesized L2, reinforces the idea that inhibitory control rather than reduced language activation can account for the bilingual advantage found in the present study. Moreover, we showed that the reduced

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[4] A multifaceted characterization of the role of each language for a multilingual person, including e.g. speed of lexical access, size of the vocabulary, written and oral comprehension (Bahrick et al., 1994; Meisel, 2007).

Stroop effect observed in bilinguals was due to a smaller Inhibition effect (incongruent minus neutral condition) in bilingual than in monolingual individuals, a further argument in favour of stronger inhibition in bilinguals than in monolinguals. However, whether the smaller interference effect observed in the incongruent condition for bilingual as compared to monolingual individuals was due to more efficient inhibition and/or a different activation level for L1 depending on the use of a second language remains an open question. Further investigation is needed into the functional architecture of the models of bilingual language processing. Altogether, the data from the present study are compatible with both inhibition and facilitation models. Therefore, we hypothesize that a hybrid functional architecture may give a better account for such data. Consequently, an experimental design that helps to distinguish between inhibitory and activation mechanisms, is needed in future research on this type of model of bilingualism. In order to disentangle the respective contribution of trained executive functions and language activation, future research should investigate executive functions using tests assumed to largely exclude the involvement of linguistic aspects (i.e. the Simon or Tower of Hanoi tasks). Such tests would allow us to isolate inhibitory control.

Conclusion

We hypothesized that frequency of L2 use, depending on linguistic environment, would have an effect on inhibitory control. We found that the use of multiple languages did play a central role for training inhibition. However, contrary to our expectations, inhibitory control was influenced not by the frequency of L2 use but, surprisingly, by the frequency of L3 use. Additionally, we showed that the duration of the immersion in an L2 environment is also a relevant predictor of inhibitory control. Furthermore, we were able to replicate a bilingual advantage employing a Stroop Colour Word task (usually used to test inhibitory control among the executive functions). Taken together, our data highlighted that those bilinguals with an additional third language appear to have a higher capacity for inhibiting interferences in cases of conflicts between competing information. Concretely, bilinguals with highly trained control mechanism seem to be able to suppress distracting information better when this information competes with the information needed to perform a cognitive task. Therefore, the present findings reinforce the idea that there is a general level of cognitive control involved in the control of multiple language use and consequently, that the capacity for inhibitory control can be improved by the use of more than one language. Further investigation with trilingual participants should be conducted in order to examine the inhibition processes in the case of multiple inter-lingual competitions. Finally, to decide between inhibition and facilitatory theories in psychology, and, in particular, to study the cognitive inhibition in a direct manner, future investigations in cognitive neuroscience should find a way to examine mechanisms of cognitive inhibition at a neurophysiological level. For this purpose, it would be relevant to perform measures of the activity of Gamma-aminobutyric acid (GABA) neurons (i.e. neurons inducing inhibition of target neurons) between brain regions assumed to support the control of other regions by turning them down. Furthermore, neuroimaging methods such as functional magnetic resonance imaging (fMRI) will help us validate inhibition models in psychology by determining which neuronal circuit supports cognitive inhibition (for the increasing number of studies examining the neural bases cognitive control in bilingual language use, see, e.g. Abutalebi, Della Rosa, Green, Hernandez, Scifo, Keim, Cappa & Costa, 2012; Garbin, Sanjuan, Forn, Bustamante, Rodriguez-Pujadas, Belloch, Hernandez, Costa & Ávila, 2010; Luk, Anderson, Craik, Grady & Bialystok, 2010; Luk, Bialystok, Craik & Grady, 2011; for reviews, see Abutalebi & Green, 2008; Luk, Green, Abutalebi & Grady, 2012). Recently, it has been argued that a fronto-subthalamic circuit, or some part thereof (e.g. inferior frontal cortices and subthalamic nucleus) could be recruited across a wide range of control mechanisms. Whether this circuit is also recruited for cognitive control remains to be studied in further cognitive neuroscientific research.

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4.2. STUDY 2: NEUROPHYSIOLOGICAL STUDY USING A STROOP & NEGATIVE PRIMING TASK

The impact of bilingualism on cognitive control has been extensively studied using behavioral measures (Costa, Hernández, et al., 2008; Heidlmayr et al., 2014; Kroll & Bialystok, 2013). However, reaction times reflect the end-product of different processes and sub-processes, and therefore present limitations for tracing the involvement of different control processes over the time. Given that one of the critical points differentiating theories of executive function is the existence or not of separable executive control processes, one needs to use recording techniques that allow us to examine the precise timing and cortical location of these processes. To date, there are only a few studies using neurophysiological techniques in the investigation of control processes in bilingualism (Coderre & van Heuven, 2014; Kousaie & Phillips, 2012b; Sullivan et al., 2014), however we have learnt a lot from a considerable number of studies using neuroimaging techniques (Abutalebi et al., 2012; Abutalebi, Rosa, et al., 2013; Crinion et al., 2006; Hervais-Adelman et al., 2011; Luk et al., 2012). Thus, important insight is yet to be gained from the study of neuronal processes underlying conflict processing and control implementation and how bilingualism impacts these processes on a temporally fine-grained scale. The present study aimed to investigate the impact of bilingualism on the time course of cognitive control processes at the neurophysiological level. More precisely, we wanted to shed light on the neurochronometry of conflict monitoring, interference suppression and conflict resolution and the impact of bilingualism at the different phases of their processing by testing the same population of bilinguals and of monolinguals in two tasks assumed to vary on the degree of cognitive demand, i.e. a Stroop task combined with a negative priming paradigm.

Experimentally, tasks considered to tap interference suppression are the Stroop task (Stroop, 1935), the Simon task (Simon & Ruddell, 1967) or the Erikson flanker task (Eriksen & Eriksen, 1974). To study cognitive inhibition and more particularly the overcoming of inhibition the negative priming paradigm, initially implemented in a Stroop task by Dalrymple-Alford and Budayr (1966), has frequently been used (Aron, 2007; Tipper, 2001). The rationale of this paradigm is that a previously inhibited stimulus component (e.g. the color word 'green' of an incongruent Stroop stimulus; **GREEN**) is temporarily unavailable and in a subsequent trial, the inhibition applied on the previous non-target stimulus component has first to be overcome in order to respond to the color now being the target (e.g. **BLUE**; in order to respond to the target color 'green', inhibition applied to this color in the previous trial needs to be overcome; for a review and for alternative explications of the negative priming effect, see MacLeod & MacDonald, 2000). Therefore, this paradigm constitutes a valuable method for studying overcoming of inhibition. In Study 2, a Stroop task combined with a negative priming paradigm were used. Based on a study conducted by Hanslmayr et al. (2008), the degree of difficulty is supposed to be higher in the negative priming compared to the incongruent Stoop condition given that the latter requires conflict processing while the former additionally requires overcoming of the inhibition applied on the previous trial. Therefore, we hypothesized that a bilingualism benefit should be more pronounced for negative priming.

In the present study (Heidlmayr, Hemforth, Moutier, & Isel, 2015), our goal was to explore the impact of bilingualism on cognitive conflict processing in young adults. Up to now, few studies have tried to disentangle which control processes are implicated in bilingual language control from those which are not, by looking at their time course at the neuronal level. Thus, in order to investigate the impact of bilingualism on the neural correlates of conflict monitoring, interference suppression and conflict resolution, an EEG study using a

Stroop task combined with a negative priming paradigm was conducted. Our study enabled us to disentangle these processes by tracing the neurodynamics of executive control processes during conflict processing using ERP and source localization analyses from the EEG signal. As for the source reconstruction analysis, based on a current theory on the functional relationship between the anterior cingulate cortex (ACC) and the prefrontal cortex (PFC; MacDonald et al., 2000), we hypothesized that ACC should monitor conflict detection and then communicate with PFC for implementation of control once the need has been identified. Thus, we predicted to find ACC activation in early time windows (especially for the N2 ERP effect) while PFC activation was supposed to emerge slightly later (N4 and the sustained potential ERP effects). Moreover, we considered bilingualism as a multidimensional rather than a categorical variable. The weights of the different dimensions inherent to bilingualism (i.e. linguistic, environmental and demographic factors) were subjected to correlation analyses.

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Neurodynamics of executive control processes in bilinguals: evidence from ERP and source reconstruction analyses

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The present study was designed to examine the impact of bilingualism on the neuronal activity in different executive control processes namely conflict monitoring, control implementation (i.e., interference suppression and conflict resolution) and overcoming of inhibition. Twenty-two highly proficient but non-balanced successive French–German bilingual adults and 22 monolingual adults performed a combined Stroop/Negative priming task while event-related potential (ERP) were recorded online. The data revealed that the ERP effects were reduced in bilinguals in comparison to monolinguals but only in the Stroop task and limited to the N400 and the sustained fronto-central negative-going potential time windows. This result suggests that bilingualism may impact the process of control implementation rather than the process of conflict monitoring (N200). Critically, our study revealed a differential time course of the involvement of the anterior cingulate cortex (ACC) and the prefrontal cortex (PFC) in conflict processing. While the ACC showed major activation in the early time windows (N200 and N400) but not in the latest time window (late sustained negative-going potential), the PFC became unilaterally active in the left hemisphere in the N400 and the late sustained negative-going potential time windows. Taken together, the present electroencephalography data lend support to a cascading neurophysiological model of executive control processes, in which ACC and PFC may play a determining role.

Keywords: executive control, bilingualism, Stroop interference, negative priming, N200, N400, ACC, PFC

Introduction

The bilingual brain can distinguish and control which language is in use. For example, individuals who communicate in more than one language are able to produce words in the selected language and to inhibit the production of words in the non-selected language. This cognitive ability to control multiple languages is assumed to rely on the

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Abbreviations: ACC, anterior cingulate cortex; LIFG, left inferior frontal gyrus; LMC, left motor cortex; LMTC, left medio-temporal cortex; LOC, left occipital cortex; LPFC, left prefrontal cortex; RIFG, right inferior frontal gyrus; RMC, right motor cortex; ROC, right occipital cortex; RPFC, right prefrontal cortex.

involvement of different cognitive processes. More generally, cognitive control, also known as executive functions, can be defined as a set of processes involved in managing processes and resources in order to achieve a goal. It is an umbrella term for the neurologically based skills involving mental control and self-regulation. Current psychological and neurobiological theories describe cognitive control either as unitary or as a system fractioned into different sub-processes. Alternatively, hybrid theoretical accounts as proposed by Miyake et al. (2000) attempt to integrate both unifying and diversifying characteristics of executive functions. Miyake et al. (2000) postulate three main executive functions, namely inhibition of dominant responses ("inhibition"), shifting of mental sets ("shifting") and monitoring and updating of information in working memory ("updating"). In the study presented in this paper, we examined cognitive inhibition but also overcoming inhibition mechanisms.

One of the key discoveries in human cognitive and brain sciences in the past 20 years is the increasing evidence from behavioral, neurophysiological, and neuroimaging studies for the plasticity of executive functions (Dahlin et al., 2008; Li et al., 2014). Psychological research has shown that the efficiency of executive control processes can be influenced among others by multiple language use (for reviews, see Costa et al., 2009; Kroll and Bialystok, 2013; Baum and Titone, 2014; Grant et al., 2014). The rationale for accounting for an improvement of executive control processes in bilinguals is the following: both languages are activated to some degree in bilingual individuals (Van Heuven et al., 1998; Hoshino and Thierry, 2011); therefore, executive control processes are regularly solicited to maintain the target language(s) in a given interactional context and to avoid persistent bidirectional cross-language influences (Blumenfeld and Marian, 2013). This constant training may make these processes more efficient in the long run. A convincing argument in favor of such a bilingualism advantage in executive functioning is empirical evidence of shorter color naming times in conflicting trials of a Stroop task (i.e., incongruency between the word of the color and the ink) in bi- than in monolinguals (Bialystok et al., 2008; Heidlmayr et al., 2014). It is however important to note that although a growing number of behavioral studies investigating control processes in bilingualism show that bilinguals perform better in many executive functions tasks (Kovacs and Mehler, 2009; Prior and Macwhinney, 2009; Gathercole et al., 2010; Hernández et al., 2010; Isel et al., 2012; Kroll and Bialystok, 2013; Kuipers and Thierry, 2013; Marzecová et al., 2013; Heidlmayr et al., 2014), a significant number of studies failed to report such an advantage of bilingualism (Morton and Harper, 2007; Paap and Greenberg, 2013; Antón et al., 2014; Duñabeitia et al., 2014; Gathercole et al., 2014; for reviews, see Costa et al., 2009; Hilchey and Klein, 2011; Kroll and Bialystok, 2013; Valian, 2015). For example, in a large sample of 252 bilingual children (age 10.5 ± 1.8 years), using both a Classic Stroop task (linguistic component) and a Numerical Stroop task (no linguistic component) to disentangle the effects that are due to language processing and those due to control processes, Duñabeitia et al. (2014) failed to observe any group differences in overall response times (RTs), as well as in Stroop (incongruent vs. congruent) and in Incongruity (incongruent vs. neutral) effect sizes, for both Classic and Numerical Stroop tasks. These findings contribute to the larger picture that a bilingual advantage is not systematically found in control tasks and they suggest that we may still have much to learn about the diversity of bilinguals we are testing. However, these findings also indicate that if a bilingual advantage is found in a Stroop task, it is not straightforward to explain it with reduced L1 language activation in bilinguals [cf. the *weaker links hypothesis* by Gollan et al. (2005)]. More importantly, the overall RT advantage in bilinguals compared to monolinguals on both congruent and incongruent trials seriously questions the conclusion that multiple language use may specifically improve performance in tasks presenting a conflict (see Hilchey and Klein, 2011 for a review). This overall RT advantage in some bilingual individuals suggests that these bilinguals are not better in conflict resolution in particular but rather that they may have either a "bilingual executive processing advantage" as proposed by Hilchey and Klein (2011) or a general enhanced capacity of processing information independently of the presence of conflicting information. The more general question we are asking here is whether there is a relationship between the use of multiple languages and the improvement of executive control efficiency, at least at some stages of second-language learning, or, more specifically, which kinds of control processes are improved by multiple language use. This assumption relates to Hilchey and Klein (2011) who claimed that many executive processes show a bilingual benefit, though not necessarily inhibition. In this paper, we will provide evidence for very specific bilingual benefits with respect to sub-processes of cognitive control.

To account for inconsistencies observed in the literature of bilingualism and executive functions, various methodological considerations can also be invoked. One of them is that until now most of the studies have used RTs as the dependent variable, which are known to result from a combination of multiple processes and sub-processes. In the present study, we recorded online electrical responses of the brain in order to trace the precise time course of the two sub-processes of interference control under investigation, namely conflict monitoring and interference suppression and their neural underpinnings. More particularly, we recorded event-related potentials (ERPs) and associated neuronal generators of ERP signatures while a group of French–German participants and their matched monolingual controls performed a Stroop task combined with a Negative priming paradigm. To study cognitive inhibition, and more particularly the overcoming of inhibition, the Negative priming paradigm, initially implemented in a Stroop task by Dalrymple-Alford and Budayr (1966), constitutes a suitable tool (Aron, 2007; for a review and for alternative explications of the Negative priming effect, see MacLeod and MacDonald, 2000). The inconsistencies observed in the literature of bilingualism and executive functions can also be the result of considering bilingualism as a categorical variable, thus masking the impact of the multiple dimensions characterizing bilingual individuals. In the present study, we used correlation analyses to embrace the multidimensional facets of bilingualism.

Over the past 20 years in cognitive psychology, neurophysiological and neuroimaging techniques have demonstrated their capacity to detect effects on a more fine-grained scale than various behavioral methods. In research on executive functions in monolinguals, three ERP signatures have been established repeatedly using different tasks. From a neurochronometric point of view, the first signature is the fronto-central N200 effect (i.e., a larger negative amplitude in the conflict compared to the non-conflict condition) assumed to reflect cognitive control (response inhibition, response conflict, and error monitoring; Boenke et al., 2009), and whose main neuronal generator was found in the ACC (Folstein and Van Petten, 2008). The second ERP signature is the centro-parietal N400 effect, usually found in Stroop studies (i.e., a larger negativity in the incongruent condition in comparison to the congruent or to the neutral condition; Liotti et al., 2000; West, 2003; Hanslmayr et al., 2008; Appelbaum et al., 2009; Bruchmann et al., 2010; Coderre et al., 2011; Naylor et al., 2012; among others). The N400 Stroop interference was interpreted to reflect higher cognitive cost in responding to stimuli in the incongruent condition – usually causing a conflict between the two sources of information, the color word and the print color – in comparison to the congruent condition. The main neuronal generators of the N400 effect were mainly found in both, the ACC and the prefrontal cortex (PFC; Liotti et al., 2000; Markela-Lerenc et al., 2003; Hanslmayr et al., 2008; Bruchmann et al., 2010). Finally, a later ERP signature was also observed, namely a late sustained negative-going potential (540–700 ms), that is a sustained fronto-central negative deflection in the incongruent condition compared to the congruent one (West, 2003; Hanslmayr et al., 2008; Naylor et al., 2012). Note that some studies also reported the inverse effect: a positive deflection, over the centro-parietal scalp (Liotti et al., 2000; West, 2003; Hanslmayr et al., 2008; Appelbaum et al., 2009; Coderre et al., 2011). The late sustained negative-going potential has been proposed to reflect either engagement of executive processes (Hanslmayr et al., 2008), conflict resolution processes (Coderre et al., 2011; Naylor et al., 2012), semantic reactivation of the meaning of words following conflict resolution (Liotti et al., 2000; Appelbaum et al., 2009), or response selection (West, 2003). Source localization has rarely been done for this late sustained negative-going potential but there is some evidence of its main neuronal generators in the middle or inferior frontal gyrus and the extrastriate cortex (West, 2003).

Recently, in an ERP study examining the impact of bilingualism on interference suppression, using Stroop, Simon, and Erikson flanker tasks, Kousaie and Phillips (2012) reported language group differences in conflict processing at the neurophysiological level (i.e., larger fronto-central N200 amplitudes and later P3 peak latencies for mono- than for bilinguals in a Stroop task) but not at the behavioral level. This finding suggests that neurophysiological measures can be more sensitive than behavioral measures. Moreover, in an ERP study also using a Stroop task, Coderre and van Heuven (2014) found a descriptively smaller N400 effect in bilinguals compared to monolinguals. In an MEG study using a Simon task, Bialystok et al. (2005) reported different correlations between the brain areas activated and the reaction times comparing bi- and monolinguals, indicating systematic differences in the activation of cognitive control areas (e.g., PFC, ACC) between the two language groups. In general, the positive correlation of faster reaction times with stronger activation in PFC and ACC in bilinguals corroborates the idea that bilingualism is associated with plasticity in cognitive control efficiency. Regarding the neuronal sources underlying bilingual language control, Abutalebi and Green (2008; see also, Green and Abutalebi, 2013) formulated a neurocognitive model constituted by a cerebral network including the ACC, the PFC, the basal ganglia (especially the caudate nucleus; see also, Crinion et al., 2006), the bilateral supramarginal gyri (SMG) and the parietal lobe (in case of high attentional load). Note that this model is widely coherent with neurocognitive models of domain-general control (MacDonald et al., 2000; Shenhav et al., 2013).

The present ERP study relies on an integrative theoretical account, i.e., the *Adaptive Control Hypothesis* model postulating that various control processes are involved in use of multiple languages (Green and Abutalebi, 2013). Our goal was to investigate the impact of bilingual experience on the neurodynamics of distinct control processes, i.e., conflict monitoring, interference suppression, overcoming of inhibition, and conflict resolution by combining a Stroop task with a Negative priming paradigm and using a high temporal resolution technique, namely electroencephalography (EEG). The experiment was administered to 22 late non-balanced French–German bilinguals and 22 French monolinguals. A correlation statistical approach, in which multiple dimensions inherent to bilingualism (i.e., linguistic, environmental, and demographic dimensions) were treated as continuous variables, was adopted to take into consideration the non-categorical nature of bilingualism.

Based on previous studies, an N200 effect (conflict detection/conflict monitoring), an N400 effect (interference suppression) and a late sustained negative-going potential (conflict resolution) should be observed for both the Stroop and Negative priming tasks. For bilinguals, smaller effect sizes were expected in the three time windows for the Stroop task and even more so for the more costly Negative priming task, when compared to monolinguals. Finally, and critically, based on current assumptions on the functional relationship between ACC and PFC (MacDonald et al., 2000), we hypothesized that ACC should monitor conflict and then communicate with PFC for implementation of control once the need has been identified. Thus, we predicted to find ACC activation especially for the early N200 and the N400 effect while PFC activation was supposed to mainly underlie the N400 component and the late sustained negative-going potential.

Materials and Methods

Participants

Forty-four right-handed (Edinburgh Handedness Inventory) participants were selected for the experiment and tested at Paris Descartes University, France. Among them were 22 successive French (L1) – German (L2) bilinguals and 22 French monolingual individuals, all of them living in France at the time of the experiment. The study was approved by the *Conseil d'évaluation éthique pour les recherches en santé* at Paris Descartes University and participants gave their written informed consent prior to participation. By their own account, participants had no history of current or past neurological or psychiatric illnesses, had normal or corrected-to-normal vision and normal color vision. They were paid 10€ per hour or received course credits for their participation. As it has been pointed out in previous studies demographic factors such as socioeconomic status (SES; Morton and Harper, 2007) and environmental factors such as expertise in music (Bialystok and DePape, 2009), video game playing (Dye et al., 2009), and actively performing sports requiring high bimanual coordination (Diamond and Lee, 2011) are all critical factors for developing executive control mechanisms. Consequently, these factors were controlled in our study (see **Table 1**).

Twenty-two successive French (L1)-German (L2) bilinguals (16 female) of an average age of 26.9 ± 5.5 years (range = 18–36 years) were tested. They were late learners of German who had started to study German from the age of 10 at secondary school in France. The mean AoA of their second language (L2) was 10.6 ± 0.7 years (range = 9–12 years). Bilingual participants had a regular use of their L2 German during the past 3 years and at present (20.9 ± 14.6% per day; see **Table 1**) and even if they were highly proficient in their L2 [self-evaluation; 1.7 ± 0.6 (1 – *high proficiency* to 5 – *low proficiency*); score language test: 83.0 ± 9.5%] they were non-balanced bilinguals. Language background data assessed with a language history questionnaire are summarized in **Table 1**.

Twenty-two monolingual French native speakers (13 female) of an average age of 25.5 ± 4.4 years (range = 19–39 years) who had had little use of languages other than their L1 during the past 3 years and at present (0.6 ± 0.9% per day; see **Table 1**) were selected as the monolingual control group.

Stimuli

An adapted version of the original Stroop task (Stroop, 1935) was used in the experiment. The task consisted of manually responding to the print color of stimuli in four different conditions, namely congruent, incongruent, negative priming, and neutral. In the congruent condition, the meaning of the color word and the print color matched (ROUGE$^{\text{red}}$), while in the incongruent and negative priming conditions they did not (ROUGE$^{\text{red}}$). In the negative priming condition, an incongruent stimulus (trial n) was preceded by an incongruent trial (trial n-1) serving as the negative prime: in trial n-1 the color word that had to be inhibited ('red' in ROUGE$^{\text{red}}$) was equal to the print color which was to name in trial n ('red' in BLEU$^{\text{blue}}$). Therefore, the inhibition affecting the color 'red' in trial n-1 needed to be overcome to correctly respond to the print color in trial n. In the congruent, incongruent and negative priming conditions, the following four color words were presented in L1, French: ROUGE$^{\text{red}}$, BLEU$^{\text{blue}}$, JAUNE$^{\text{yellow}}$, VERT$^{\text{green}}$ and their translation equivalents in L2, German: ROT$^{\text{red}}$, BLAU$^{\text{blue}}$, GELB$^{\text{yellow}}$, GRÜN$^{\text{green}}$. In the neutral condition, four non-color words were presented in the same print colors as in the congruent and incongruent conditions (CHAT$^{\text{cat}}$) in L1, French: CHAT$^{\text{cat}}$, CHIEN$^{\text{dog}}$, MAIN$^{\text{hand}}$, PIED$^{\text{foot}}$ and their translation equivalents in L2, German: KATZE$^{\text{cat}}$, HUND$^{\text{dog}}$, HAND$^{\text{hand}}$, FUSS$^{\text{foot}}$. The stimulus words, written in capitals of font "Calibri" in font size 48, were presented individually against a black background in the center of the screen.

Procedure

Participants were seated in front of the computer screen (14" screen) and instructed to perform a manual color response task, that means they had to indicate as fast and as correctly as possible

TABLE 1 | Language background and environmental factors.

	Bilinguals (n = 22)		Monolinguals (n = 22)		p
	Mean	**SD**	**Mean**	**SD**	
Age [years]	26.9	(5.5)	25.5	(4.4)	n.s.
Freq. of daily language use other than L1 [%]	26.6	(13.9)	0.6	(0.9)	<0.001
Freq. of daily L2 use [%]	21.4	(14.1)	0.5	(0.8)	<0.001
Freq. of daily L3 use [%]	4.8	(6.4)	0.2	(0.6)	<0.01
L2 PS [1: high – 5: low]	1.7	(0.6)	–	–	–
L2 PO [%]	83.0	(9.5)	–	–	–
Music practice [hour/week]	0.9	(2.2)	1.1	(2.2)	n.s.
Sport practice [hour/week]	1.6	(2.1)	1.4	(2.0)	n.s.
Vid/Comp game play [hour/week]	0.9	(2.1)	2.1	(4.4)	n.s.

Results from the evaluation of the participants' language background and environmental factors such as music practice, high coordination sports, or computer/video game play are shown. Mean and SD are indicated for each factor. Freq., frequency; L2 PO, proficiency in L2 German – objective (Test: DAF – Deutsch als Fremdsprache); L2 PS, proficiency in L2 German – subjective (self-evaluation on a scale from 1 – high proficiency to 5 – low proficiency); Vid/Comp game play, Video and Computer game play.

the print color of the stimulus word by pressing one of the four color-coded response buttons (keys *d*, *f*, *j*, and *k*). The color-finger-assignment was counterbalanced between-subjects. Stimuli were presented with *E-Prime 1.2* (Psychological Software Tools, Pittsburgh, PA, USA). Each trial started with a fixation-cross presented in the center of the screen for 500 ms (**Figure 1**), which was then replaced by the stimulus word. The stimulus remained visible until one of the four color response keys was pressed (online RT) but maximally for 1500 ms. Then followed an inter trial interval (ITI) of 2300 ms figuring a black screen. After the first 1000 ms of the ITI, a blink sign (a symbolized eye) was displayed for 300 ms. Participants were instructed to limit eye blinks to the interval starting with the blink sign until the end of the ITI in order to reduce motor artifacts on the ERP response.

In order to enable the participants to learn the color-key correspondences, two training blocks of 40 trials each were presented before starting the ten experimental blocks. If accuracy was below 80% after the second training block, training was repeated. For bilinguals, five experimental blocks featured words in German, the five other blocks featured words in French. For monolinguals all blocks consisted of words in French but only five were selected for further analysis. In order to compare Language groups, only the procedure for L1 (French) blocks is presented as follows. Each block consisted of 72 trials, consisting of 24 congruent, 12 incongruent, 12 negative priming and 24 neutral stimuli, presented in a pseudo-randomized order. Online RT was defined as the interval between the onset of the stimulus word and the button press. Responses before 200 ms or after 1500 ms were coded as missing. We averaged the RTs for correct responses for each experimental condition across participants and across items. RTs outside a range of 2 standard deviation from the mean per participant were excluded from the statistical analysis.

Analysis of Behavioral Data

Two-way repeated measures analysis of variances (ANOVAs), including the within-subjects factor Condition (congruent, incongruent, negative priming, neutral) and the between-subjects factor Language group (bilingual, monolingual) were conducted for the dependent variables Error rate and RT. Moreover, in order to compare the behavior in the two languages of the bilingual participants, two-way repeated measures ANOVAs were conducted including the within-subjects factors Condition (congruent, incongruent, negative priming, neutral) and Language (L1, L2) for the dependent variables Error rate and RT.

ERP Recording

Electroencephalography was recorded using a Geodesics 64-channel sensor net and the software NetStation (Electrical Geodesics Inc., Eugene, OR, USA). All channels were referenced online against Cz. For data analysis, channels were re-referenced to an average reference. Electrode impedances were kept below 50 kΩ. Data were recorded at a sampling rate of 500 Hz, with an online 0.1–80 Hz frequency bandpass filter. Then, data were filtered offline with a 0.5–35 Hz bandpass filter.

ERP Analysis

The continuous EEG were segmented into epochs from 200 ms pre-stimulus until 1500 ms post-stimulus onset and baseline corrected with the baseline set from −200 to 0 ms. Only trials with correct responses that were not contaminated by ocular or other movement artifacts were kept for further data analysis. Automatic detection was run followed by a visual inspection of the segmented data. The total percentage of rejected trials were distributed equally over the four conditions ($F < 1$; congruent: 37.3 ± 16.9%, neutral: 38.3 ± 15.4%, incongruent:

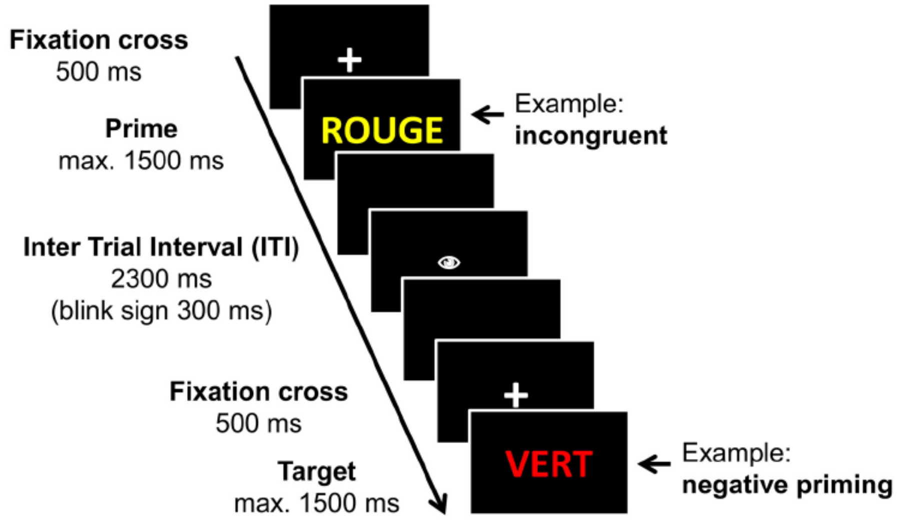

FIGURE 1 | Timing of a trial. The timing of a trial in the manual version of a Stroop task is displayed. Two succeeding trials are given in order to demonstrate the Negative priming procedure.

38.0 ± 16.9%, negative priming: 37.6 ± 16.1%). This is true for rejected trials due to erroneous behavioral responses (congruent: 3.2 ± 3.0%, neutral: 3.3 ± 3.5%, incongruent: 3.8 ± 4.2%, negative priming: 3.6 ± 3.8%) as well as due to artifacts in the signal (congruent: 34.0 ± 16.7%, neutral: 35.0 ± 14.9%, incongruent: 34.1 ± 16.4%, negative priming: 34.0 ± 15.6%). In each experimental condition, the ERP activity was then averaged over stimuli and over participants (i.e., grand average ERP). Statistical analyses were conducted for three ERP signatures for which the time windows were selected based on previous ERP studies of executive functioning and adjusted by visual inspection of the grand averages: N200 (200–300 ms), Stroop N400 (400–500 ms), and a late sustained negative-going potential (540–700 ms). For the three selected intervals, analyses were conducted on the ERPs from selected electrodes. All analyses were quantified using the multivariate approach to repeated measurement and followed a hierarchical analysis schema. In order to allow for an examination of hemispheric differences, the data recorded at the lateral recording sites were treated separately from the data recorded at the midline electrode sites. Analyses are presented for the Stroop effect (incongruent vs. congruent condition) and the Negative priming effect (negative priming vs. congruent condition) because our hypotheses were centered on these effects.

For the lateral recording sites, for each time window, a four-way repeated measures ANOVA including the within-subjects factors Condition (Stroop: incongruent, congruent; Negative priming: negative priming, congruent), the topographical variables Hemisphere (left, right) and Region (anterior, posterior) and the between-subjects factor Language group (bilingual, monolingual) was conducted. Four regions of interest (ROIs) resulting from a complete crossing of the Region and Hemisphere variables were defined: left anterior (F7, F3, FT7, FC3), right anterior (F8, F4, FT8, FC4), left posterior (CP5, P7, P3, O1), and right posterior (CP6, P8, P4, O2).

For the midline electrodes, a three-way repeated measures ANOVA including the within-subjects factors Condition (Stroop: incongruent, congruent; Negative priming: negative priming, congruent), Electrode (Fz, Cz, Pz) and the between-subjects factor Language group (bilingual, monolingual) was run for each of the three time windows of interest. Moreover, given that we had a hypothesis on differences between Language groups based on previous studies, two-way repeated measures ANOVAs including the factors Condition (Stroop: incongruent, congruent; Negative priming: negative priming, congruent), and Language group (bilingual, monolingual) were run on each of the three midline electrodes in each time window. The dependent variable was the voltage amplitude averaged over each interval of interest. The Greenhouse–Geisser correction (Greenhouse and Geisser, 1959) was applied when evaluating effects with more than 1 degrees of freedom in the numerator. *Post hoc* pairwise comparisons at single electrode sites were performed using a modified Bonferroni procedure (Keppel, 1991). A significance level of 0.05 was used for all statistical tests and only significant results are reported.

Source Analyses

Hanslmayr et al. (2008) proposed a dipole (localizing neuronal source activity) model for a Stroop task containing eight discrete dipoles in fixed locations: LOC/ROC (visual stimulus processing), LMC/RMC (manual response), ACC (cognitive control), LMTC (color processing), LPFC/RPFC (cognitive control). This eight dipoles model is based on theoretical assumptions of cognitive processes and their neural correlates involved in the execution of a Stroop task and has been tested and partially confirmed by Bruchmann et al. (2010). Here, we applied a 10-regional sources model including the sources proposed by Hanslmayr et al. (2008) plus two further neuronal generators found to be involved in Stroop processing, that is the LIFG/RIFG (cognitive control, inhibition; Peterson et al., 2002), in order to capture the largest number of neuronal sources (**Table 2**). Due to heterogeneous findings of peak activation in the ACC for a Stroop task in the previous literature and in order to improve the variance explained by the source model, the coordinates for the regional source in the ACC were chosen from a meta-analysis on a Stroop task (Laird et al., 2005).

TABLE 2 | Source localization coordinates.

Brain region	Abbrevations	BA	Talairach coordinates			Reflected process
			x	*y*	*z*	
Left occipital cortex	LOC	17	−21	−79	−1*	Visual stimulus processing
Right occipital cortex	ROC	17	21	−79	−1*	Visual stimulus processing
Left medio-temporal cortex	LMTC		−45	−55	9*	Color processing
Left motor cortex	LMC	4	−36	−17	59*	Manual response
Right motor cortex	RMC	4	36	−17	59*	Manual response
Anterior cingulate cortex	ACC	32	1	16	38Δ	Cognitive control, attention, motor modulation, response selection
Left prefrontal cortex	LPFC	46/6	−32	22	57*	Cognitive control
Right prefrontal cortex	RPFC	46/6	32	22	57*	Cognitive control
Left inferior frontal gyrus	LIFG	44	−45	7	14†	Cognitive control, inhibition
Right inferior frontal gyrus	RIFG	44	44	8	13†	Cognitive control, inhibition

For discrete source localization of scalp ERPs in a Stroop task, Talairach coordinates have been taken from the following studies: *Hanslmayr et al., 2008; ΔLaird et al., 2005; †Peterson et al., 2002; *For extended regions, coordinates for peak activation specifically found in a Stroop task are indicated. BA, Brodman area.*

In the present study, discrete source analysis was done with the Brain Electrical Source Analysis program (BESA, version 5.3., Megis Software, Heidelberg, Germany). Regional sources were seeded in fixed locations while their orientations were a free parameter. This theoretical model of regional sources explained 75.3% of the variance. In order to trace the neuronal generators of scalp ERP effects, statistical analyses using bootstrap confidence intervals (99%) were conducted using BESA (version 5.3.) and the Waveforms toolbox for Matlab. The bootstrapping procedure was applied to investigate source activation underlying the Stroop effect (incongruent vs. congruent) and the Negative priming effect (negative priming vs. congruent) on each neuronal source in our theoretical model (ACC, LPFC, RPFC, LIFG, RIFG, LMC, RMC, LOC, ROC, LMTC). The source ERP amplitude between two conditions was considered to be significantly different ($p < 0.01$) for intervals in which the confidence interval (99%) of the difference wave did not include zero.

Correlation Analyses

As we consider that taking bilingualism as a categorical variable and therefore conducting ANOVAs is a necessary but not a sufficient approach to explore the impact of bilingualism on neuronal measures of cognitive control, we additionally conducted correlation analyses between linguistic background measures and behavioral and neurophysiological Stroop and Negative priming effect[1] sizes in bilinguals, with the following factors: the frequency of L2 and of L3 use, L2 proficiency, duration of immersion in an L2 environment, and age of immersion.

Results

Behavioral Results

Behavioral data are shown in **Table 3** and **Figure 2**. For Error rates, the two-way repeated measures ANOVA did not reveal a main effect of Condition ($F < 1$), nor a main effect of Language group ($p > 0.10$), or a Condition by Language group interaction ($F < 1$). For RTs, the ANOVA showed a main effect of Condition [$F(3,126) = 38.54$, MSE = 1099.94, $p < 0.001$, $\eta_p^2 = 0.479$], reflecting that RTs were longer in the incongruent (669 ± 105 ms) compared to the congruent condition [613 ± 94 ms; Stroop effect; $F(1,42) = 68.6$, MSE = 2013.8, $p < 0.001$, $\eta_p^2 = 0.620$] as well as compared to the neutral condition [628 ± 93 ms; $F(1,42) = 61.97$, MSE = 1660.6, $p < 0.001$, $\eta_p^2 = 0.596$]. Moreover, RTs were longer in the negative priming (658 ± 107 ms) compared to

TABLE 3 | Behavioral data.

	Monolinguals		Bilinguals				Monolinguals		Bilinguals			
	L1 – ERR [%]		L1 – ERR [%]		L2 – ERR [%]		L1 – RT [ms]		L1 – RT [ms]		L2 – RT [ms]	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Congruent	2.4	(2.1)	3.5	(3.4)	3.8	(3.2)	623	(98)	603	(91)	600	(92)
Incongr.	3.0	(2.3)	3.8	(4.3)	4.7	(5.3)	683	(98)	655	(112)	629	(100)
Neg. prim.	3.0	(2.3)	4.2	(4.5)	3.6	(4.3)	669	(116)	648	(99)	627	(104)
Neutral	2.4	(2.3)	3.9	(4.4)	3.6	(3.8)	635	(92)	622	(95)	617	(96)

Error rates (ERR) [%] and response times (RTs) [ms] in the four experimental conditions (congruent, incongruent, negative priming, neutral) are indicated with standard deviation (SD) in parentheses for the two Language groups in their L1 and for bilinguals also in their L2. ERR, error rate; RT, response time; SD, standard deviation.

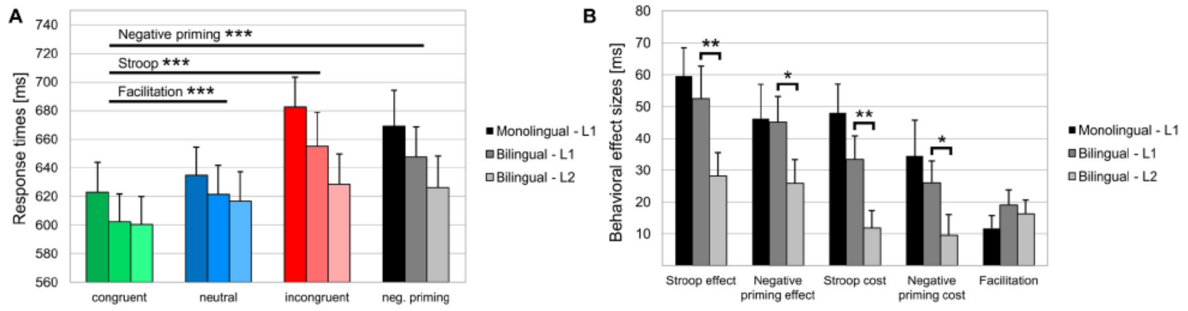

FIGURE 2 | Behavioral data. (A) Mean response times [ms] and the SEM in the congruent, neutral, incongruent and negative priming experimental conditions and **(B)** behavioral effect sizes are displayed for the two Language groups in their L1 and for bilinguals also in their L2. ERR, error rate; RT, response time. $^{*}p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$.

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[1] In case of more negative average amplitudes in the incongruent or negative priming compared to the congruent condition, effect sizes were calculated by subtracting the values in the incongruent or negative priming condition from the values in the congruent condition.

the congruent condition [613 ± 94 ms; Negative priming effect; $F(1,42) = 45.8$, MSE = 1999.8, $p < 0.001$, $\eta_p^2 = 0.522$] as well as compared to the neutral condition [628 ± 93 ms; $F(1,42) = 21.12$, MSE = 1908.5, $p < 0.001$, $\eta_p^2 = 0.335$]. RTs were shorter in the congruent (613 ± 94 ms) compared to the neutral condition [628 ± 93 ms; Facilitation effect; $F(1,42) = 23.61$, MSE = 439.8, $p < 0.001$, $\eta_p^2 = 0.360$]. Finally, there was no main effect of Language group ($F < 1$) nor a Condition by Language group interaction ($F < 1$).

Comparing the behavioral data in the L1 and L2 of bilinguals no differences were found for error rates. For RTs, however, there was a main effect of Language [$F(1,21) = 4.44$, MSE = 1879.4, $p < 0.05$, $\eta_p^2 = 0.175$] indicating that averaged RTs were shorter in L2 (618 ± 96 ms) compared to L1 (632 ± 97 ms). There was also a Condition by Language interaction [$F(3,63) = 6.64$, MSE = 337.04, $p < 0.01$, $\eta_p^2 = 0.240$] indicating that the Stroop effect (incongruent vs. congruent) was larger in L1 (52 ± 48 ms) compared to L2 (28 ± 35 ms; $p < 0.01$); furthermore, the Negative priming effect (negative priming vs. congruent) was larger in L1 (45 ± 38 ms) compared to L2 (26 ± 35 ms; $p < 0.05$). Finally, the *post hoc* analyses also showed that the Stroop cost (incongruent vs. neutral) was larger in L1 (33 ± 35 ms) compared to L2 (12 ± 26 ms; $p < 0.01$); similarly, the Negative priming cost (negative priming vs. neutral) was larger in L1 (26 ± 32 ms) compared to L2 (10 ± 31 ms; $p < 0.05$).

Electrophysiological Results

Stroop Effect

In the time-window 200–300 ms, neither the four-way ANOVA on lateral electrodes nor the three-way ANOVA on midline electrodes revealed any main effect or interaction involving the factors Condition or Language group. Two-way repeated measures ANOVAs on each of the midline electrodes did not reveal any Condition by Language group interaction or main effect of Language group.

In the time window 400–500 ms, the four-way ANOVA on lateral electrodes revealed a main effect of Condition [$F(1,42) = 13.46$, MSE = 0.15, $p < 0.001$, $\eta_p^2 = 0.243$] reflecting a more negative amplitude in the incongruent compared to the congruent condition (Stroop effect). Moreover, a Condition by Region interaction [$F(1,42) = 5.98$, MSE = 0.85, $p < 0.05$, $\eta_p^2 = 0.125$] indicated that the N400 Stroop effect was observed over the posterior scalp. Similarly, the three-way ANOVA on midline electrodes revealed a Condition by Electrode interaction [$F(2,84) = 4.11$, MSE = 1.5, $p < 0.05$, $\eta_p^2 = 0.089$] indicating that the N400 Stroop effect (incongruent more negative than congruent) was only significant at the Pz electrode [$F(1,43) = 6.43$, MSE = 0.75, $p < 0.05$, $\eta_p^2 = 0.130$]. Two-way repeated measures ANOVAs revealed a Condition by Language group interaction on the Cz electrode [$F(1,42) = 4.57$, MSE = 0.59, $p < 0.05$, $\eta_p^2 = 0.098$], reflecting that the N400 Stroop effect was significant for monolinguals ($p < 0.05$; **Figure 3B**) but not for bilinguals ($p > 0.10$; **Figure 3A**; see also **Figure 3C**). Given that we had a strong hypothesis on the modulation of the N400 effect between the two groups based on previous studies, we then conducted further two-way ANOVAs on electrodes neighboring the Cz electrode to determine whether the N400 effect was significant over other electrodes. These analyses revealed a significant Condition (incongruent, congruent) by Language group (bilingual, monolingual) interaction also on the electrode C1. A small ROI including the electrodes Cz and C1 was created and we conducted a three-way ANOVA [Condition (incongruent, congruent), Electrode (Cz, C1), Language group (bilingual, monolingual)] which revealed a significant Condition by Language group interaction [$F(1,42) = 5.92$, MSE = 0.804, $p < 0.05$, $\eta_p^2 = 0.123$]. *Post hoc* analyses revealed that there was a tendency toward a significant effect of Condition over this ROI for monolinguals ($p = 0.078$) while it was not significant in bilinguals ($p > 0.10$).

In the time-window 540–700 ms, neither the four-way ANOVA on lateral electrodes nor the three-way ANOVA on midline electrodes revealed any main effect or interaction involving the factors Condition or Language group. Two-way repeated measures ANOVAs revealed a main effect of Condition on the Cz electrode, reflecting a more negative amplitude in the incongruent compared to the congruent condition [Stroop effect; $F(1,42) = 5.69$, MSE = 0.570, $p < 0.05$, $\eta_p^2 = 0.119$]. Moreover, a Condition by Language group interaction on the Cz electrode [$F(1,42) = 4.7$, MSE = 0.57, $p < 0.05$, $\eta_p^2 = 0.101$], indicated that the late sustained negative-going potential was only significant in monolinguals ($p < 0.01$; **Figures 3A–C**). To test whether the interaction effect between Condition and Language Group was significant over electrodes neighboring Cz, additional two-way ANOVAs were run. These analyses revealed a Condition by Language group interaction also on electrodes C1 and FC1. Creating a small ROI with these three electrodes we conducted a three-way ANOVA [Condition (incongruent, congruent), Electrode (Cz, C1, FC1), Language group (bilingual, monolingual)], which revealed a significant Condition by Language group interaction [$F(1,42) = 6.77$, MSE = 1.094, $p < 0.05$, $\eta_p^2 = 0.139$]; *Post hoc* analyses showed that the incongruent condition was significantly more negative compared to the congruent condition in monolinguals ($p < 0.001$) while there was no significant difference in bilinguals ($F < 1$).

Source localization analyses collapsed over Language group ($n = 44$) revealed a significant difference between the incongruent and the congruent condition (Stroop effect) in the ACC (80–530 ms). In the PFC, however, the Stroop effect was significant later and only in the left hemisphere, LPFC (80–130, 300–530, 630–920 ms). Moreover, the Stroop effect was present in the following sources: LIFG (230–290 ms), RIFG (220–260 ms), RMC (230–270, 410–550 ms), LMTC (20–110, 160–240, 410–450 ms). Looking at the source activity of sources involved in control processes (ACC, LPFC, RPFC, LIFG, RIFG; **Figure 4**) groupwise, the following differences between bilinguals and monolinguals were found: in bilinguals the Stroop effect was significant ($p < 0.01$) in the ACC (160–570 ms), LPFC (310–520, 650–830 ms), and LIFG (420–530 ms). In monolinguals however, the Stroop effect was significant in LPFC (90–150, 400–510 ms), RPFC (560–680 ms), LIFG (250–300 ms), and RIFG (140–230, 380–440 ms) but not in the ACC.

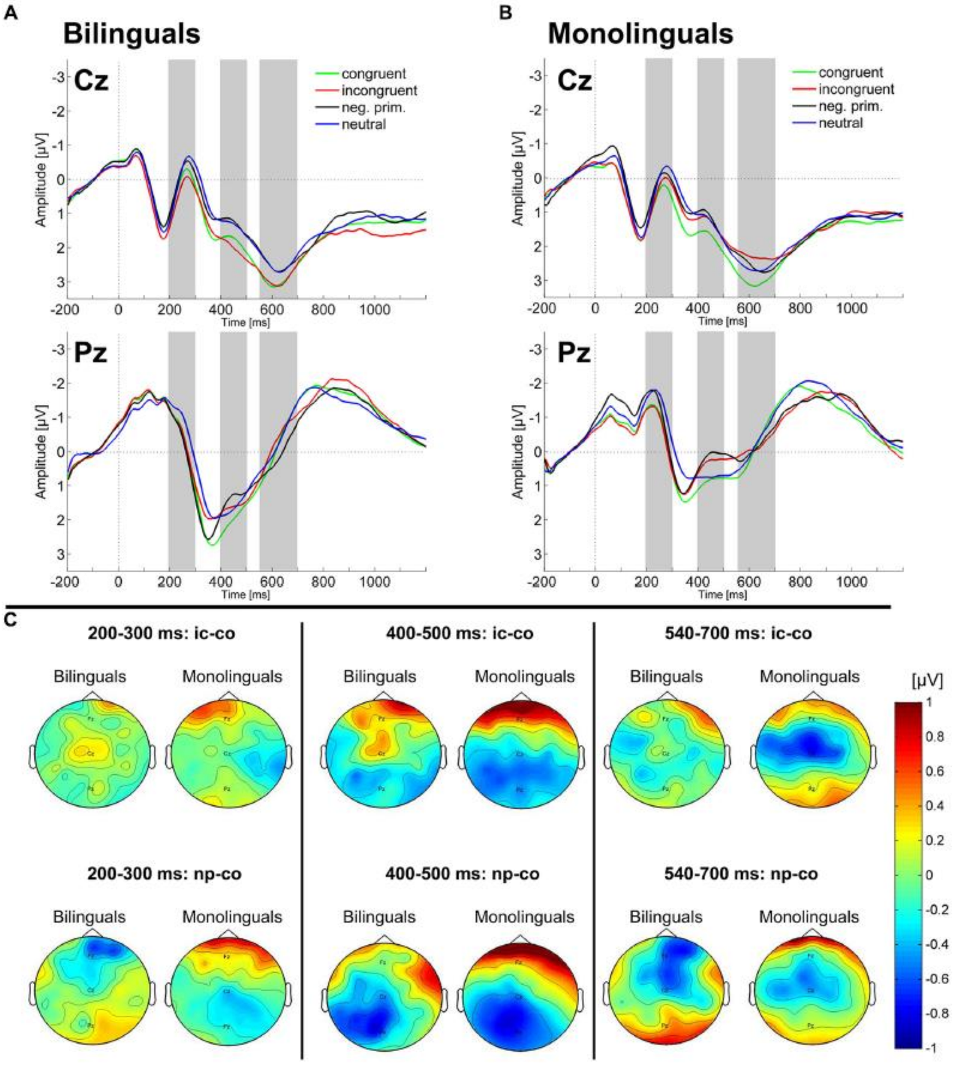

FIGURE 3 | Scalp ERPs. The ERP in the four experimental conditions (congruent, neutral, incongruent, and negative priming) on the Cz and Pz electrodes are plotted for **(A)** bilinguals and **(B)** monolinguals. The gray bars indicate the time intervals which were used for statistical analysis of the mean amplitude. **(C)** Topographies of amplitude differences [µV] for the Stroop effect (incongruent – congruent; ic-co) and the Negative priming effect (negative priming – congruent; np-co) are shown for bilinguals and monolinguals in each of the three time windows.

Negative Priming Effect

In the time-window 200–300 ms, the four-way ANOVA on lateral electrodes did not show any main effect or interaction involving the factors Condition or Language group. The three-way ANOVA on midline electrodes revealed a significant Condition by Electrode by Language group interaction [$F(2,84) = 3.9$, $MSE = 0.93$, $p < 0.05$, $\eta_p^2 = 0.085$]. *Post hoc* analyses revealed a marginally significant Condition by Language group interaction on the Fz electrode [$F(1,42) = 3.65$, $MSE = 0.79$, $p = 0.063$, $\eta_p^2 = 0.08$] that was due to an effect inversion between Language groups (the negative priming condition being more negative compared to the congruent condition in bilinguals, while this effect was reversed in monolinguals). The two-way repeated measures ANOVAs on each of the three midline electrodes only revealed a main effect of Condition on the Cz electrode [$F(1,42) = 8.17$, $MSE = 0.231$, $p < 0.01$, $\eta_p^2 = 0.163$], reflecting a larger negativity in the negative priming condition compared to the congruent one (Negative priming effect).

In the time-window 400–500 ms, the four-way ANOVA revealed a significant Condition by Region interaction [$F(1,42) = 14.63$, $MSE = 0.64$, $p < 0.001$, $\eta_p^2 = 0.258$], indicating that the negativity was larger in the negative priming condition compared to the congruent one over the posterior electrodes. The three-way ANOVA on the midline electrodes

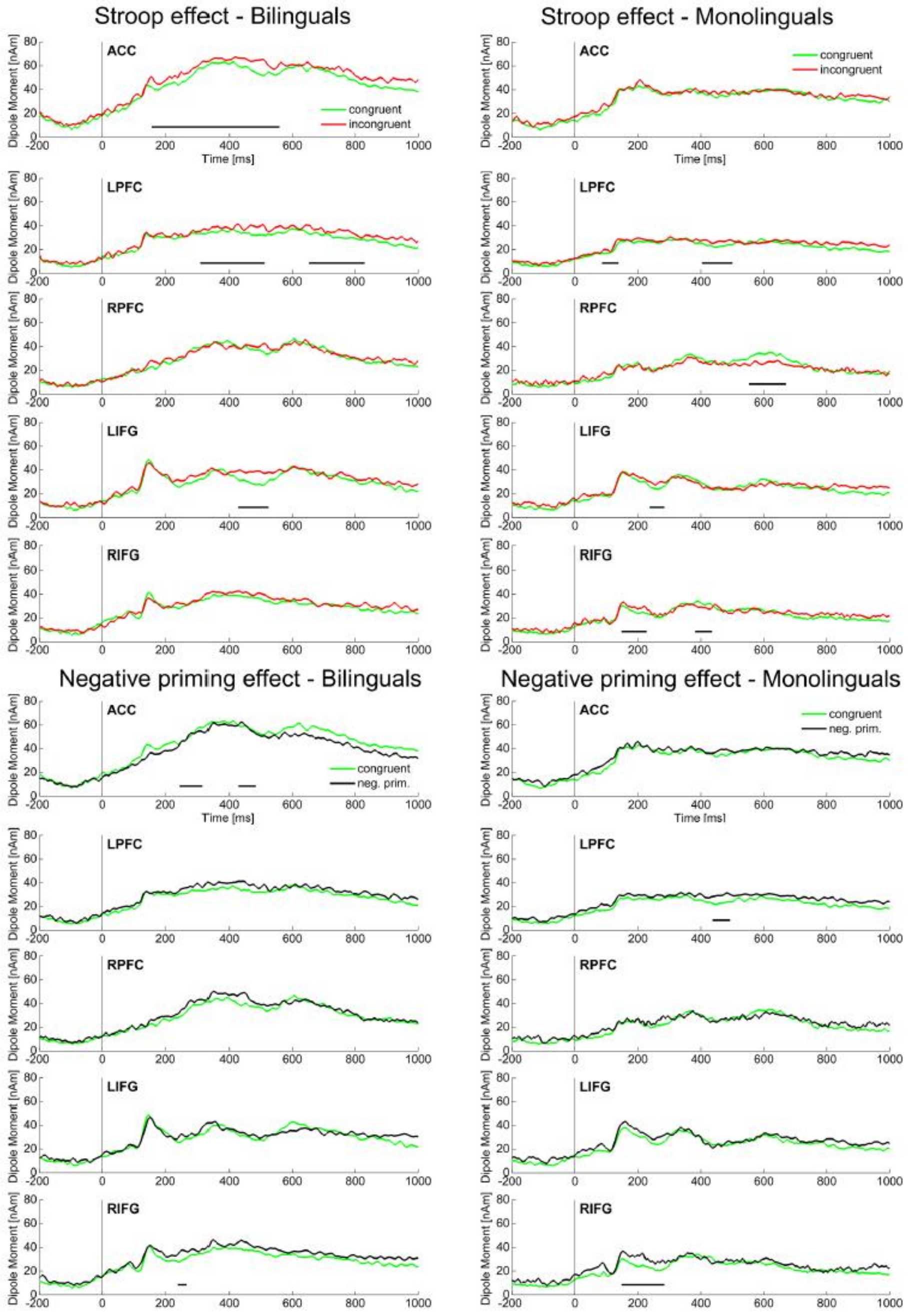

FIGURE 4 | Source ERPs. Source activity in the ACC, LPFC, RPFC, LIFG, and RIFG is displayed for the Stroop effect (incongruent vs. congruent) and the Negative priming effect (negative priming vs. congruent) for the two Language groups in their L1. Intervals with a significant difference ($p < 0.01$) in source ERP amplitude between the two conditions are marked with a black bar. ACC, anterior cingulate cortex; LPFC, left prefrontal cortex; RPFC, right prefrontal cortex; LIFG, left inferior frontal gyrus; RIFG, right inferior frontal gyrus.

revealed a main effect of Condition [$F(1,42) = 9.84$, MSE = 0.84, $p < 0.01$, $\eta_p^2 = 0.190$], in that the amplitude of the negativity in the negative priming condition was larger than the one found in the congruent condition. Moreover, there was a Condition by Electrode interaction [$F(2,84) = 5.13$, MSE = 1.59, $p < 0.05$, $\eta_p^2 = 0.109$] reflecting that the amplitude was more negative in the negative priming compared to the congruent condition on the centro-parietal electrodes Cz [$F(1,43) = 12.8$, MSE = 0.43, $p < 0.001$, $\eta_p^2 = 0.230$; **Figures 3A–C**] and Pz [$F(1,43) = 16.4$, MSE = 0.75, $p < 0.001$, $\eta_p^2 = 0.276$]. Two-way repeated measures ANOVAs did not reveal any main effect or interaction involving the factor Language group.

In the time-window 540–700 ms, the four-way ANOVA (Condition, Hemisphere, Region, Language group) revealed a significant Condition by Region interaction [$F(1,42) = 5.32$, MSE = 0.55, $p < 0.05$, $\eta_p^2 = 0.112$], indicating that over the anterior scalp, the negative priming condition was more negative compared to the congruent condition while over the posterior scalp the negative priming condition was more positive as compared to the congruent condition. The three-way ANOVA (Condition, Electrodes, Language group) revealed a significant main effect of Condition [$F(1,42) = 5.55$, MSE = 0.74, $p < 0.05$, $\eta_p^2 = 0.117$], indicating that the amplitude in the negative priming condition was more negative as compared to the congruent condition (**Figures 3A–C**). Two-way repeated measures ANOVAs on each of the three midline electrodes did not reveal any main effect or interaction involving the factor Language group.

Source localization analyses collapsed over Language group ($n = 44$) revealed a significant difference between the negative priming and the congruent condition (Negative priming effect) in the ACC (250–310, 440–490 ms). In the PFC, however, the Negative priming effect underlying the scalp ERP effects became significant later and only in the left hemisphere, LPFC (40–100, 420–490 ms). Moreover, the Negative priming effect was present in the following sources: RIFG (170–290 ms), LOC (250–360, 400–440 ms), RMC (450–550 ms). Looking at the source activity of sources involved in control processes (ACC, LPFC, RPFC, LIFG, RIFG; **Figure 4**) groupwise, the following differences between bilinguals and monolinguals were found: in bilinguals the Negative priming effect was significant ($p < 0.01$) in the ACC (240–320, 420–480 ms) and RIFG (250–280 ms). In monolinguals however, the Negative priming effect was significant in LPFC (430–490 ms) and RIFG (150–290 ms) but not in the ACC.

Correlation Analyses

One linguistic factor turned out to modulate the neurophysiological effect size in bilinguals: the frequency of L2 use was negatively correlated with the N400 Negative priming effect over the Pz electrode [$r(22) = 0.424$, $p < 0.05$; **Figure 5A**]. That means, the more bilinguals used their second language on a daily basis, the smaller was the N400 Negative priming effect.

Discussion

The present study aimed to investigate the impact of bilingual experience on the neurochronometry of different control processes, i.e., control monitoring, interference suppression, overcoming of inhibition, and conflict resolution. For this purpose, a combined Stroop/Negative priming task was administrated to 22 late highly proficient but non-balanced French–German bilinguals and 22 French monolinguals while event-related brain potentials were recorded. At the neurophysiological level, a bilingualism benefit was found as revealed by reduced ERP effects in bilinguals in comparison to monolinguals, but this benefit was only observed in the Stroop task and was limited to the N400 and the late sustained potential ERP components. Moreover, and critically, we were able to show a differential time course of the activation of ACC and PFC in executive control processes. While the ACC showed major activation in the early time windows (N200 and N400) but not in the latest time window (late sustained negative-going potential), the PFC became unilaterally active in the left hemisphere in the N400 and late sustained negative-going potential time windows.

Event-Related Potentials

On the neurophysiological level, three effects were expected: a central N200 effect (more negative amplitude in the negative

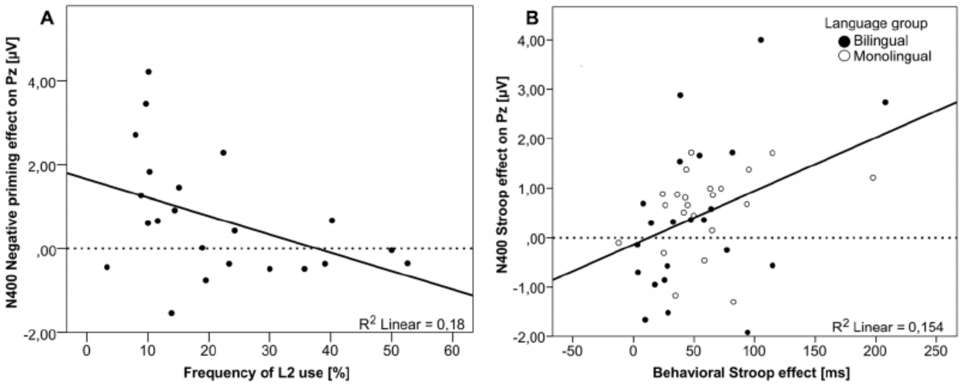

FIGURE 5 | Correlation analyses. (A) The negative correlation between the Frequency of L2 use and the N400 Negative priming effect (congruent − negative priming) size in bilinguals ($n = 22$) on the Pz electrode, and **(B)** the positive correlation between the behavioral Stroop effect (incongruent − congruent) size and the neurophysiological N400 Stroop effect (congruent − incongruent) size on the Pz electrode (both Language groups collapsed; $n = 44$) are plotted.

priming and the incongruent conditions compared to the congruent condition in the 200–300 ms time window), a centro-parietal N400 effect (more negative amplitude in the negative priming and the incongruent conditions compared to the congruent condition in the 400–500 ms time window) and a fronto-centrally distributed late sustained negative-going potential (more negative amplitude in the negative priming and the incongruent conditions compared to the congruent condition in the 540–700 ms time window). We predicted to find reduced Stroop and Negative priming interference effects – reflecting reduced cost in conflict processing – in bilinguals compared to monolinguals.

An N200 effect was only observed for the Negative priming task (negative priming minus congruent). The increased negativity reported in the incongruent condition could be explained by an inhibition account (Aron, 2007) postulating that responses in a negative priming condition are usually delayed due to the necessity to overcome previously applied inhibition in order to access response-relevant information. However, note that we did not find longer latency in the incongruent condition in comparison with the congruent one. Hence, the N200 Negative priming effect may reflect overcoming of inhibition and/or high demand in conflict monitoring, which are processes that plausibly take place in negative priming trials but not in incongruent trials. Furthermore, an N400 effect was found for the Negative priming task (negative priming more negative than congruent; N400 Negative priming effect) as well as in the Stroop task (incongruent more negative than congruent; N400 Stroop effect). This observation replicates previous observations of a sensitivity of the N400 time window to Stroop interference (Liotti et al., 2000; Markela-Lerenc et al., 2003; Hanslmayr et al., 2008). Similarly, in the present study, the more negative N400 amplitude in the incongruent Stroop condition may reflect underlying inhibitory processes. Furthermore, consistent with previous findings the N400 effect was larger for the more costly task, i.e., Negative priming (N400 Negative priming effect; negative priming more negative than congruent).

The critical question of the present study concerned group differences: we observed smaller effect sizes for bilinguals in comparison with monolinguals but only for the N400 and the late sustained negative-going potential ERP effect in the Stroop task. No group difference was found in the early time window of the N200. It is plausible that a smaller Stroop N400 effect reflects reduced orthographic interferences that might be due to more efficient inhibition of interfering information. Similarly, Coderre and van Heuven (2014) have also reported a smaller Stroop N400 effect in bilinguals compared to monolinguals. Note that some authors label this incongruency effect P3 effect; for example Kousaie and Phillips (2012) found that the Stroop P3 peaked earlier in bilinguals as compared to monolinguals. Finally, a larger Stroop N400-like effect has been reported for children with learning disabilities as compared to age-matched controls, which was interpreted to reflect interference control deficits (Liu et al., 2014).

Correlation analyses between behavioral and neurophysiological effect sizes corroborate the idea that a smaller Stroop effect reflects better inhibitory capacities, in that an increasing behavioral Stroop effect was found to be reflected by an increasing N400 effect [at Pz electrode; $r(44) = 0.393$, $p < 0.01$; **Figure 5B**] in the present study. Concerning the reduced late sustained negative-going potential effect observed in the Stroop task for bilinguals as compared to monolinguals, it is not easy to find a good interpretation as there is a lack of consensus on the functional significance of this effect. Some authors have proposed that the late sustained negative-going potential may reflect stages of conflict resolution. Thus, the group differences we reported for the N400 and the late sustained negative-going potential might suggest that the bilinguals tested in our study may have less cost in dealing with the conflict present in a Stroop task. Taken together, for the Stroop task, a bilingual advantage has been found in the stages of conflict processing that are thought to reflect control implementation involving interference suppression (N400 effect) and conflict resolution (late sustained negative-going potential).

However, surprisingly, and against our predictions on task complexity, we failed to show both at the behavioral and neurophysiological levels a bilingual advantage in the Negative priming task, though considered a more complex task. Hence, the similarity of behavioral and electrical responses in the two groups in the Negative priming task could be an indicator that control processes specifically involved in this task may not be more efficient due to bilingual experience. Nonetheless, correlation analyses revealed a modulation of Negative priming effect size with frequency of L2 use (positive correlation), which indicates that bilingualism experience does have a certain impact on processes taking place in a Negative priming task, such as overcoming of inhibition, but that considering bilingualism as a categorical variable might not be sufficiently sensitive to capture this effect. Moreover, the heterogeneity in the monolingual group should not be neglected, in that ‘monolingual’ individuals nonetheless do have some basic foreign language experience – even if the extent was controlled to be as little as possible. This heterogeneity should, however, influence Stroop effects and Negative priming effects equally.

The differences between language groups observed for Stroop but not for Negative priming effect sizes, though unexpected, may actually corroborate the idea that the bilingual advantage in the Stroop task is mainly due to differences in control efficiency but not to the lower activation of the linguistic component in bilinguals. The *weaker links hypothesis* by Gollan et al. (2005) predicts similar effects for Stroop and Negative priming effects sizes. Thus, if the use of more than one language and consequently the reduced frequency of use of each single language in bilinguals were the main cause for their Stroop benefits, a comparable reduction of the effect size should have been observed for the Negative priming effect sizes in the present study, which was not the case. Consequently, the differences between the two language groups appear to be attributable to differences in the efficiency of specific control processes involved in the different tasks.

To account for the absence of a group difference for the neurophysiological N400 effect in the Negative priming task despite the observation of (1) a bilingualism advantage in the N400 Stroop task, i.e., a less complex task, (2) a negative correlation between frequency of L2 use and magnitude of the Negative priming N400 effect in bilinguals, and (3) a stronger involvement of ACC in bilinguals than in monolinguals, we propose the following interpretation: we suggest that the specificity of the experimental constraints imposed by the Negative priming design is playing a major role here. Whereas in the Stroop task, incongruent trials were equally preceded by congruent or by neutral trials, in the Negative priming paradigm, a negative priming trial was always preceded by an incongruent trial due to the rational of the paradigm (overcoming of an information that was inhibited in an incongruent previous trial). Thus, we propose that the absence of a group effect in the negative priming condition at the neurophysiological level could be due to the fact that the monolingual individuals were already in a mode of inhibition when they encountered a negative priming trial. Consequently, they benefited from a local advantage so that they were able to manage the complexity of the Negative priming task as well as the bilinguals. The bilinguals, on the other hand, may have benefited less from this local advantage as their inhibitory capacities are already at ceiling. This *post hoc* explanation of a finding that turned out to be inconsistent with our primary hypothesis of task complexity, may shed a new light on the functioning of control processes. Indeed, it suggests that when we put monolinguals in an inhibition mode, they become able to manage a complex control task as efficiently as bilinguals. This means that, at least at short-term, the executive control processes involved for performing the Negative priming task were sufficiently efficient in monolinguals for reaching the same level of control as that observed in bilinguals usually assumed to present an advantage in cognitive control. At least at short-term, an advantage may also be found in monolinguals when they work in an inhibition mode. This would argue for neurophysiological plasticity of the cognitive control processes under investigation in the present study. Further work should attempt to disentangle the respective role of second language use and mode of information processing on the improvement of executive control functioning, and explore the long-term impact of these factors in mono- and bilingual individuals.

Source Localization: Proposal of a Cascading Neurophysiological Model of Executive Control Processes in Bilinguals

As already found in previous studies (Folstein and Van Petten, 2008; Hanslmayr et al., 2008; Bruchmann et al., 2010; among others), we found that the ACC as well as the PFC were main neuronal generators of the N200 and N400 Stroop and Negative priming effects in the present study (**Figures 4** and **6**). Moreover, the present data allow us to precise the time course of these main generators. While in the N200 and the N400 time windows, the ACC showed high activation and was a main neuronal generator for scalp interference effects, its activation did not play a major role in the late sustained negative-going potential time window (for similar findings on transient ACC activation in conflict trials, see Carter et al., 2000). The PFC, on the contrary, was a main neuronal generator for scalp interference effects in the N400 and late sustained negative-going potential time windows. This pattern of ACC and PFC activation was mainly driven by the bilingual group. Thus, our data suggest that the ACC may play a major role in initiating transient control as necessary when conflict has been detected while the PFC would be more active for implementing the control when the need has been detected (i.e., applying inhibition and conflict resolution), which is in line with previous findings and theoretical accounts (Dreher and Berman, 2002; Botvinick, 2007; Carter and Van Veen, 2007; Abutalebi and Green, 2008; Shenhav et al., 2013). However, it has been shown that there are functional subdivisions of the ACC that behave differently according to task demands and are affected differently by task practice (Leung et al., 2000; Milham and Banich, 2005).

Concerning the group differences observed in source activation but not in behavioral data in the present study, note that a similar pattern of results has been reported in a previous MEG study (Bialystok et al., 2005). In this MEG study using a Simon task, Bialystok et al. (2005) found that underlying neuronal processes in the Simon task were different for bilinguals compared to monolinguals even if the groups did not differ in response speed. Bialystok et al. (2005) found that the language group differences did not only consist in the differential intensity of activation of the areas involved in performing the Simon task but even more so in the pattern of areas that were involved. Beyond differences in other areas, in bilinguals as well as monolinguals the incongruency effect was reflected by activation in the left PFC and ACC (among others) but this activation was stronger in bi- than in monolinguals. It is particularly interesting that our data are compatible with these observations since we were using a different task, the Stroop task, which is however, comparable to the Simon task in that both involve conflict processing and are thought to necessitate interference suppression amongst the executive functions. Our results are in line with the Bialystok et al.'s (2005) in two ways, both of which concern especially the differential involvement of the ACC in the two groups: (1) the differences in the pattern of control region involvement in bilinguals and monolinguals in performing the Stroop task, and (2) the more salient difference in source activation between the incongruent and the congruent condition in bilinguals as compared to monolinguals, a group difference that is however, not reflected at the behavioral level. These findings indicate that multiple language use impacts the activation in the neuronal basis of domain-general control processes not only quantitatively in potentially leading to more efficient control but also seems to qualitatively modulate the activation of the control network. The absence of a behavioral bilingual advantage in the present study may be due to the fact that behavioral measures constitute the end-product of a combination of subprocesses, which could mask some effects that are difficult to be traced because of intrinsic heterogeneity of bilingual participants (for similar findings, see Gathercole et al., 2010; Coderre and van Heuven, 2014; Duñabeitia et al., 2014; however, other studies did find a bilingual advantage in a Stroop task, see Bialystok et al., 2008; Heidlmayr et al., 2014; Yow and Li, 2015; for a review, see Paap and Greenberg, 2013).

Further investigation of the neuronal processes in bilingualism should include fMRI studies to obtain higher spatial accuracy as

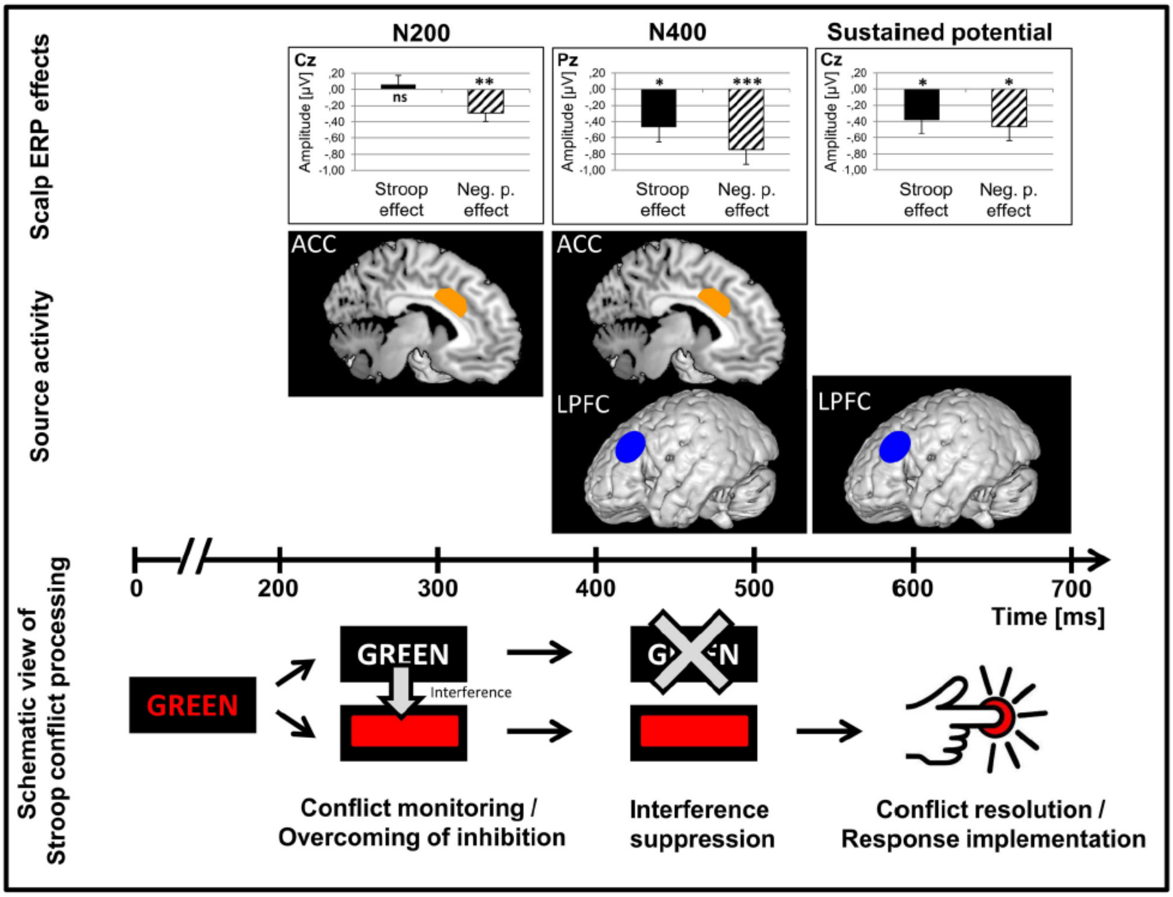

FIGURE 6 | Schematized view of control processes and the neuronal underpinnings in a Stroop task. Scalp ERP effect sizes (Stroop effect, Negative priming effect) for each of the three ERP components (N200, N400, late sustained negative-going potential) and the main underlying neuronal sources for the scalp ERP effects are plotted. A schematized view of the time course of Stroop conflict processing is displayed below. Data are collapsed over Language group ($n = 44$). ACC, anterior cingulate cortex; LPFC, left prefrontal cortex. $^{*}p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$. Image credit for the schematized image of pressing a button: Download Clipart (2013).

well as functional connectivity analyses. Indeed, Crinion et al. (2006) suggested that subcortical regions like the left caudate may play a crucial role in monitoring and controlling the language in use. Consequently, the description of the neuronal network supporting executive control processes in language control cannot escape a better understanding of how different cortical (ACC, PFC among others) and subcortical (left caudate) brain areas communicate in monitoring and controlling the language in use.

Summing up, bilinguals seem to benefit from higher efficiency in their neuronal and cognitive processing of control implementation, namely interference suppression and conflict resolution because of their experience in handling two languages on a daily basis. However, there appears to be less of an advantage in conflict monitoring, at least for the type of bilinguals selected and the paradigm used in the present study. Moreover, this advantage of bilingualism was not observed in the Negative priming task. Yet, future research using different neuroimaging techniques should help to give a more detailed account of the current findings in trying to characterize the relation between conflict monitoring and interference suppression and the impact of bilingualism in each of these processes. Identifying the neuronal sources of these processes as well as their connectivity with higher precision would be of greatest interest. Moreover, the requirement to deal with linguistic conflict or complexity is not limited to the case of bilingualism but control processing is also crucial in handling within-language interference, as it has been shown for ambiguity resolution in the domains of semantics (Rodd et al., 2010), and syntax (January et al., 2009), but also for phonology, and phonetics (e.g., tongue twisters, Acheson and Hagoort, 2014). Whether control processing involved in managing between- versus within-language interference is quantitatively and/or qualitatively different is still unclear. Further behavioral and neuroscientific research will be necessary to advance our understanding of the similarities and differences between bilingual and monolingual language control.

Conclusion

The present findings are partially in line with previous studies demonstrating a bilingual advantage on interference control, and more specifically interference suppression. We were able to show a bilingual advantage in the Stroop task but only in the N400 and the late sustained negative-going potential time windows. Unexpectedly, however, we failed to find a bilingual benefit in the Negative priming task, though considered a more complex task. We proposed that this lack of an effect may be due to the specific task demands of the Negative priming task. Nevertheless, the current results are compatible with the hypothesis that bilingualism enhances efficiency of domain-general cognitive control because the neuronal network of general control and the multiple language control network largely overlap (Abutalebi and Green, 2008). Interestingly, we were able to confirm an activation of ACC and PFC which Dreher and Berman (2002) have already established in an fMRI study using a task-switching paradigm, with the Stroop and the Negative priming paradigm, allowing to test conflict monitoring and interference suppression. One of the innovative contributions of our study is the demonstration that there are differential time courses of the involvement of ACC and PFC in conflict processing. While the ACC showed major activation in early time windows (N200 and N400) but not in the later one (late sustained negative-going potential), the PFC became active in the left hemisphere in the N400 time window and in the late sustained negative-going potential time windows. This chronometric finding adds an important piece to the puzzle of theories of the functional relationship between ACC and PFC postulating that ACC would participate in conflict monitoring and communicate with the lateral PFC that would implement cognitive control (MacDonald et al., 2000; Shenhav et al., 2013; for a schematic overview, see **Figure 6**). Further research, combining fMRI and ERP measures, will be necessary to study with both high temporal and spatial resolution the neurochronometry of the cognitive control network, involving amongst others the ACC and the PFC. Moreover, our results are a valuable contribution to the bilingualism literature in that we were able to show that there are specific control processes that seem to be involved in and improved by multiple language use while this may not be the case for other control processes. However, caution is at order before drawing firm conclusions regarding the relation between multiple language use and efficiency of executive functioning. In the present study, the contradictory findings between tasks challenge the view of a systematic bilingualism advantage. On the contrary, the task differences can be explained by assuming that the efficiency of executive functions could also be improved in monolinguals when the experimental design leads them to expect a need for inhibition, thus encouraging an inhibition strategy. Thus, in future research, it will be relevant to apply a battery of tasks tapping into different cognitive and executive functions while taking into consideration the multidimensional characteristics of bilingualism. Such an approach will improve our understanding of the impact of multiple language use on the plasticity of the cognitive control efficiency.

To sum up, the main contribution of the present study is three-fold: our findings indicate that (1) studying the neurodynamics of conflict processing with high temporal resolution can help us disentangling different sub-processes of conflict processing, (2) cascading models appear to capture essential aspects of the time course of neuronal source activation in conflict processing and (3) bilinguals seem to perform better on specific control processes while performing equally to monolinguals on others. Hence, our findings are a valuable contribution to the executive function literature in general and to new theoretical accounts of neurodynamics of executive control in bilingualism in particular.

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5. CONTROL IN NON-LINGUISTIC TASKS: EYE MOVEMENT CONTROL

5.1. STUDY 3: NEUROPHYSIOLOGICAL STUDY USING AN ANTISACCADE TASK

After having provided insight into control processing in a control task involving a linguistic component, i.e. the combined Stroop and negative priming task, in Study 2, the third study was launched in order to investigate the influence of bilingualism in non-linguistic control. More efficient control in bilingual compared to monolingual individuals has previously been observed in non-linguistic tasks (Bialystok et al., 2008; Colzato et al., 2008; Costa et al., 2009; Costa, Hernández, et al., 2008; Kovács, 2009; Marzecová et al., 2013; Prior & MacWhinney, 2010; Singh & Mishra, 2015), which is mostly interpreted to corroborate the theoretical position that domain-general control is involved in the control of multiple language use. In Study 3 (Heidlmayr, Doré-Mazars, Aparicio, & Isel, submitted), an antisaccade task was used in order to study the impact of bilingualism on executive control in a non-linguistic task involving motor control. The antisaccade task is a task that allows for studying the volitional control of action (Munoz & Everling, 2004). Participants are instructed to carry out either an automatic eye movement towards a visual target (prosaccade) or to suppress this automatic eye movement and effectuate a saccade into the opposite direction (antisaccade), depending on the color of the instructional cue preceding the target stimulus. The antisaccade task specifically allows for studying the control processes of conflict monitoring and response inhibition, as well as the switching-related shifting of attention and hence this task is suitable for studying the bilingualism impact on these different control processes as well as their interplay. In a modified antisaccade task, Bialystok, Craik and Ryan (2006) as well as Bialystok and Viswanathan (2009) observed that bilinguals performed better than monolinguals in measures of inhibitory control (or ‘interference suppression’), switching (or ‘cognitive flexibility’) and response inhibition, but the emergence of a bilingual advantage varied as a function of age. Moreover, in a saccadic countermanding task, an oculomotor control task, bilinguals with high compared to those with low second language proficiency have been shown to have a behavioral advantage (Singh & Mishra, 2015), an advantage that has however been attributed to improved performance monitoring rather than inhibitory control.

In Study 2, evidence for a cascading relation between ACC and PFC activity in cognitive control has been found. However, this evidence was based on a temporal relation between activity in the ACC, which is thought to be involved in conflict monitoring, and PFC, which is thought to be involved in control implementation involving inhibition, i.e. the ACC was active in the N2 and N4 time windows and the PFC slightly later, in the N4 and late sustained potential (LSP) time windows. The temporal relation of activity in different sources is a good indicator of a relation between the earlier active source influencing the later active source, but to obtain a more solid picture of a causal relation between sources, here a more complex approach was chosen, i.e. dynamic causal modelling (DCM) which allows to investigate effective connectivity. DCM takes into consideration not only temporal relations but also the topographical distribution, structural connectivity or the effects of external perturbations. Consequently, effective connectivity analyses were employed in Study 3 in order to obtain insight into, amongst others, the mutual influence between ACC and PFC activity.

Due to the reduced resolution of the figures in the submitted manuscript of Study 3, a second set of figures of high resolution is added right after the manuscript of Study 3.

PLOS ONE

Multiple language use influences oculomotor task performance: Neurophysiological evidence of a shared substrate between language and motor control

--Manuscript Draft--

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Corresponding Author:	Karin Heidlmayr Paris Descartes - Sorbonne Paris Cité University Boulogne-Billancourt Cedex, FRANCE
Keywords:	bilingualism; conflict monitoring; Response Inhibition; antisaccade task; N2/P3; effective connectivity; ACC; PFC
Abstract:	In the present electroencephalographical study, we asked to which extent executive control processes are shared by both the language and motor domain. The rationale was to examine whether executive control processes whose efficiency is reinforced by the frequent use of a second language can lead to a benefit in the control of eye movements, i.e. a non-linguistic activity. For this purpose, we administrated to 19 highly proficient late French-German bilingual participants and to a control group of 20 French monolingual participants an antisaccade task, i.e. a specific motor task involving control. In this task, an automatic saccade has to be suppressed while a voluntary eye movement in the opposite direction has to be carried out. Here, our main hypothesis is that an advantage in the antisaccade task should be observed in the bilinguals if some properties of the control processes are shared between linguistic and motor domains. ERP data revealed clear differences between bilinguals and monolinguals. Critically, we showed an increased N2 effect size in bilinguals, thought to reflect better efficiency to monitor conflict, combined with reduced effect sizes on markers reflecting inhibitory control, i.e. cue-locked positivity, the target-locked P3 and the saccade-locked presaccadic positivity (PSP). Moreover, effective connectivity analyses (dynamic causal modelling; DCM) on the neuronal source level indicated that bilinguals rely more strongly on ACC-driven control while monolinguals on PFC-driven control. Taken together, our combined ERP and effective connectivity findings may reflect a dynamic interplay between strengthened conflict monitoring, associated with subsequently more efficient inhibition in bilinguals. Finally, L2 proficiency, motivation to improve L2 proficiency, and immersion experience all constitute relevant factors of language background that predict efficiency of inhibition. To conclude, the present study provided ERP and effective connectivity evidence for domain-general executive control involvement in handling multiple language use, leading to a control advantage in bilingualism.
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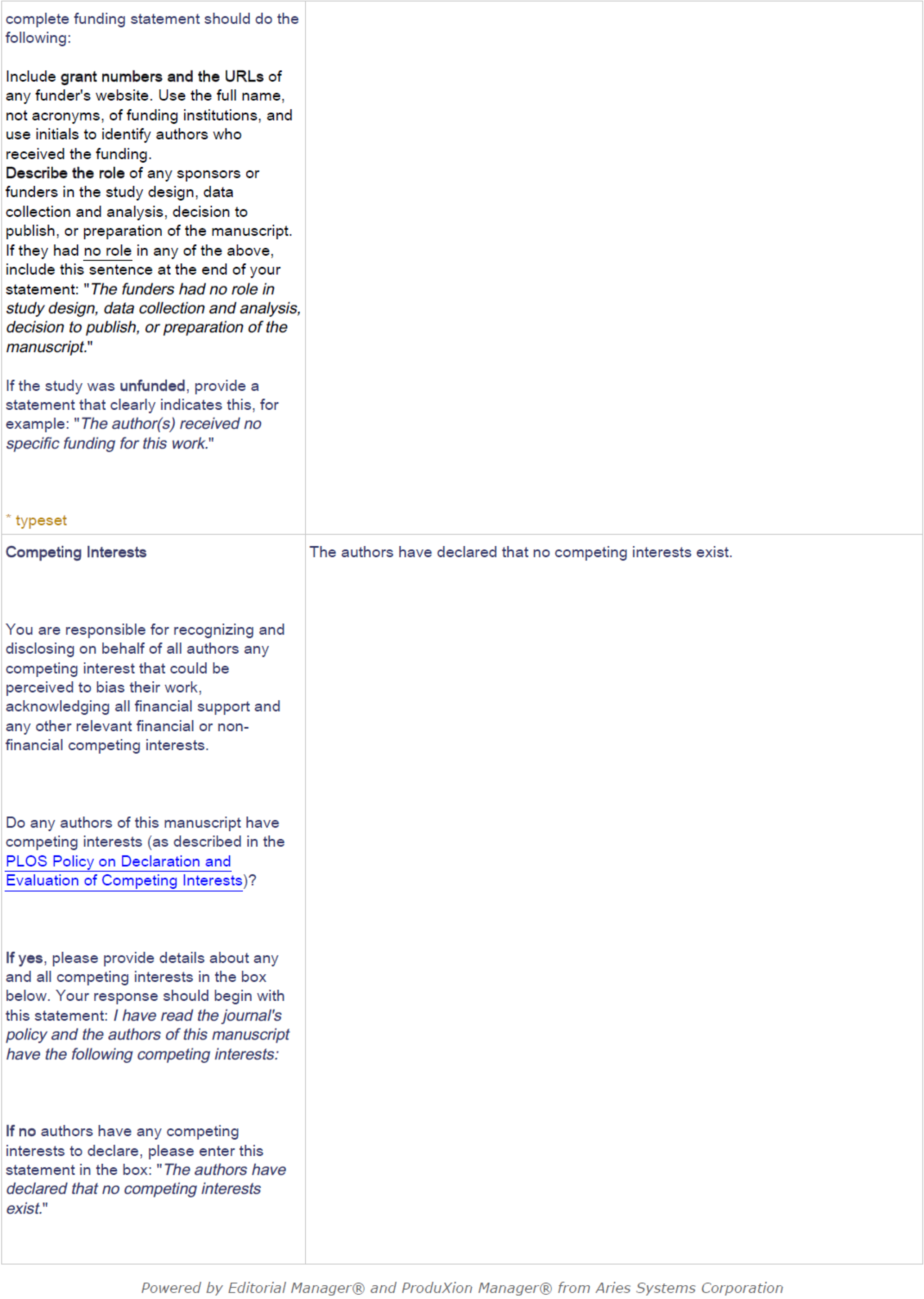

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Please describe where your data may be found, writing in full sentences. **Your answers should be entered into the box below and will be published in the form you provide them, if your manuscript is accepted.** If you are copying our sample text below, please ensure you replace any instances of XXX with the appropriate details.	We hereby declare that all data used in this paper are freely available online for other researchers to use and analyze as they see fit, provided reference to this paper is made in resulting writings. Data files include participant information, EEG and eye tracking data. The data can be found when using the following DOI:

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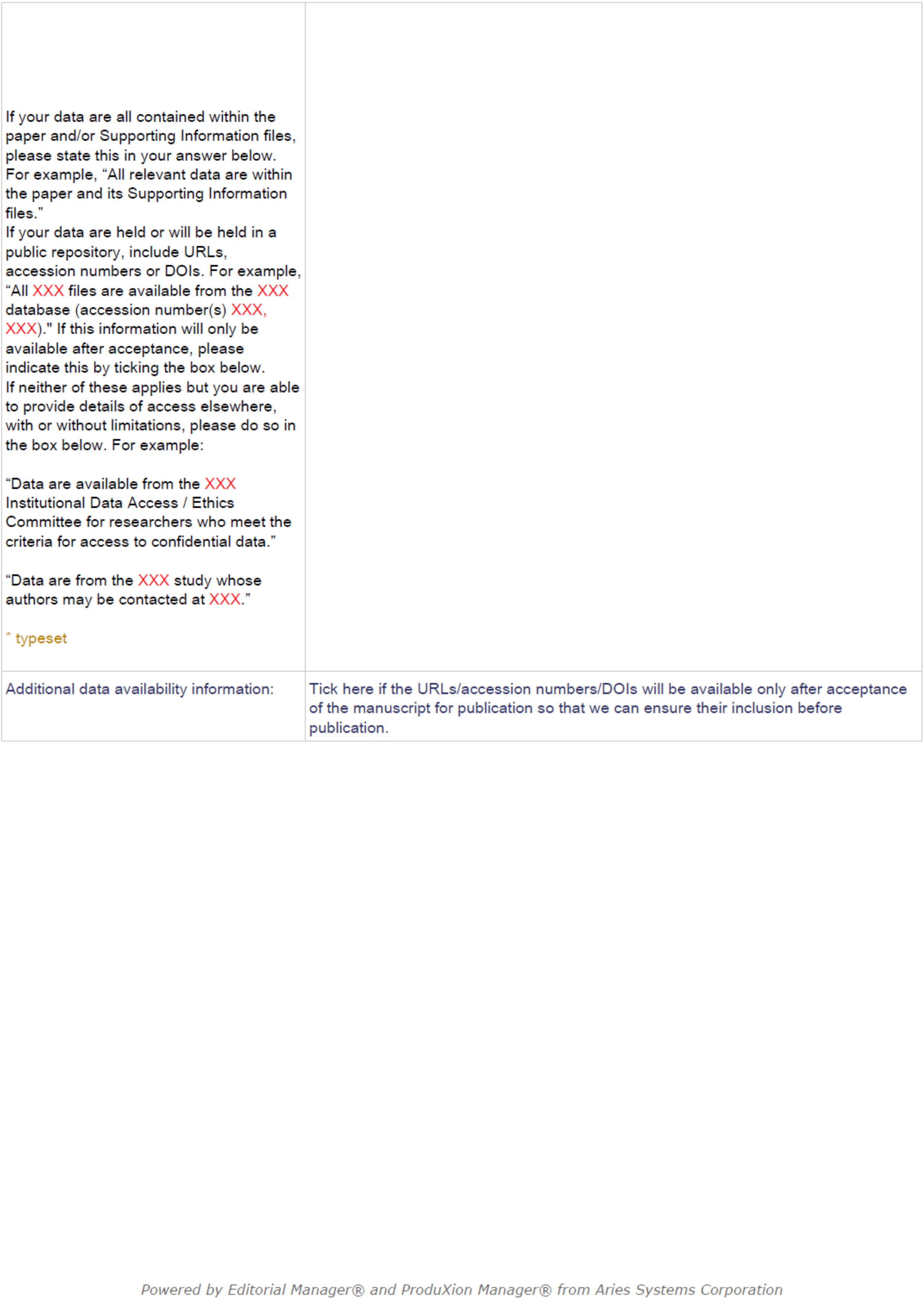

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Multiple Language Use Influences Oculomotor Task Performance: Neurophysiological Evidence of a Shared Substrate between Language and Motor Control

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Abstract

In the present electroencephalographical study, we asked to which extent executive control processes are shared by both the language and motor domain. The rationale was to examine whether executive control processes whose efficiency is reinforced by the frequent use of a second language can lead to a benefit in the control of eye movements, i.e. a non-linguistic activity. For this purpose, we administrated to 19 highly proficient late French-German bilingual participants and to a control group of 20 French monolingual participants an antisaccade task, i.e. a specific motor task involving control. In this task, an automatic saccade has to be suppressed while a voluntary eye movement in the opposite direction has to be carried out. Here, our main hypothesis is that an advantage in the antisaccade task should be observed in the bilinguals if some properties of the control processes are shared between linguistic and motor domains. ERP data revealed clear differences between bilinguals and monolinguals. Critically, we showed an increased N2 effect size in bilinguals, thought to reflect better efficiency to monitor conflict, combined with reduced effect sizes on markers reflecting inhibitory control, i.e. cue-locked positivity, the target-locked P3 and the saccade-locked presaccadic positivity (PSP). Moreover, effective connectivity analyses (dynamic causal modelling; DCM) on the neuronal source level indicated that bilinguals rely more strongly on ACC-driven control while monolinguals on PFC-driven control. Taken together, our combined ERP and effective connectivity findings may reflect a dynamic interplay between strengthened conflict monitoring, associated with subsequently more efficient inhibition in bilinguals. Finally, L2 proficiency, motivation to improve L2 proficiency, and immersion experience all constitute relevant factors of language background that predict efficiency of inhibition. To conclude, the present study provided ERP and effective connectivity evidence for domain-general executive control involvement in handling multiple language use, leading to a control advantage in bilingualism.

Keywords: Bilingualism; conflict monitoring; response inhibition; antisaccade task; N2/P3; effective connectivity, ACC, PFC.

1. Introduction

1.1. Executive control and neuroplasticity in bilingualism

Individuals need to constantly adapt to environmental constraints and neuroplasticity allows for this adaptive capacity over the lifespan [1,2]. Permanent adaptation is amongst others required in linguistic interaction, especially if an individual has acquired competence in more than one language. In multilingualism, significant neuroplastic changes have been observed in language learning or immersion experience, both of which are highly challenging situations, in linguistic and cognitive terms [3,4]. Structural changes found with multiple language use were, e.g. grey matter volume increases with intense language interpretation studies [5], increases of grey matter density with improving L2 proficiency in immersion [6], or white matter connectivity increases with intense classroom language training [7]; for a review, see [4]. Importantly, in sustained multiple language use, not only the neurocognitive language system but also the involved control processes need to adapt in order to meet the cognitive requirements. Indeed, second-language users of a language have different control demands than native speakers, due to the reduced automaticity of the second language, the simultaneous activation of languages [8–12] and the bidirectional cross-language influences [13–15]. Therefore, psycholinguistic models of language control have to discuss the different control processes and to ask to which extent these processes are shared by different cognitive functions (language, memory, attention). A longstanding debate has opposed theories, which proposed that control processes are domain-general [16–20] to others postulating that these processes are at least to a large degree specific to each domain [21]. In the present study, we asked whether some control processes are shared by both the language and the motor domain. The rationale was to examine at the neurophysiological level whether executive control processes whose efficiency is assumed to be reinforced by the frequent use of a second language can lead to a benefit for realizing a motor task involving control, i.e. the antisaccade task. This question on the functional architecture of executive control processes across different functions is directly related to the broader theoretical framework of embodied/grounded cognition. Embodied cognition theories feed the debate on the main question of the shared vs. distinct nature of linguistic and sensory-motor processing in handling natural language. Increasing neuroimaging and neurophysiological evidence supports the view of a distributed interactive systems account (cf. “embodied cognition” or “grounded cognition”; [22,23], e.g. the coactivation of classical language and motor regions during action word processing; [24], or the influence of word reading on motor control; [25]). As for executive control, manifold empirical evidence lends support to the theoretical accounts claiming a shared nature of (domain-general) control between cognitive domains, i.e. showing overlapping neuronal activation for linguistic and non-linguistic control [26–28], as well as improved performance in bi- and multilinguals in both linguistic and non-linguistic executive control tasks [29–35]; there is however no unanimity in this regard, for reviews, see [34,36–39]. These findings constitute major arguments in favor of models postulating domain-general control processes to be involved in the control over multiple language use. It is important to note that the inconsistency that some studies do and others fail to show a bilingualism advantage in executive control processes may be explained by the fact that bi- or multilinguals vary on different dimensions, e.g. second language proficiency, frequency of first and second language use, or the type of interactional context (for a discussion, see [34], but also [31]). As a consequence, different profiles of bilingualism may involve specific sets of control processes. *Conflict monitoring* performance in non-verbal tasks has been found to be improved in bilingualism in a behavioral study using the Attentional Network Task (ANT) [40], an advantage that has been found in a neurophysiological study to be especially strong in bilinguals with good control over their language switches [41], or in bilinguals with high second language proficiency, as observed in a neurophysiological study using a saccadic countermanding task [42]. A behavioral advantage in *response inhibition* as well as task *switching* performance was found in a modified antisaccade task in older but not in younger adult bilinguals [43]. Using the same task, a *switching* advantage was also observed in bilingual children [44]. These data collected from different age groups suggest that (1) activity-dependent long-term effects on executive function capacity vary over the lifespan, and (2) activity-dependent improvements are more likely to occur in age groups with generally lower than peak EF capacity, i.e. children and older adults. In a non-verbal task switching paradigm, Prior and MacWhinney [35] found a behavioral bilingual advantage for switching and Prior and Gollan [45] found that the benefit was strongest if bilinguals reported a high frequency of daily language switching.

More recently, intermediate theoretical positions postulating a hybrid neural architecture of executive control and its interaction with the language domain have emerged, which try to account more specifically for the relation between domain-general and domain-specific processes. One account postulates, that domain-general executive control is involved in language processing but, based on network neuroscience, it is claimed that in neurocognitive networks, e.g. the language network, there is a distinction between a network core and periphery which differentially interact with other neurocognitive networks [46]. This perspective may help identifying domain-specific and domain-general processes in language processing [46]. Similarly, however for control in non-linguistic domains, one account considers that there is an interplay between both domain-general control processes, that are shared across cognitive and motor domains, and domain-specific control processes, that are specific to the control challenges in a particular cognitive or motor domain [21]. Multiple findings on language and non-linguistic control, showing evidence for an overlap across domains for some control processes while not for others support these theoretical accounts [47,48]. To date, there is no consensus on whether executive control processes are partially or fully shared between different domains (linguistic, non-linguistic, motor).

The goal of the present electroencephalographic study was to investigate whether control processes whose efficiency can be increased by the use of multiple languages are also involved in nonlinguistic activities such as the control of eye movements. For this purpose, we administrated to highly proficient French-German bilingual participants and to a control group of French monolingual participants an antisaccade task, i.e. a task involving motor control rather than cognitive control, in which an automatic saccade needs to be suppressed and a voluntary eye movement in the opposite direction needs to be carried out. The main hypothesis of our study is that a behavioral and/or a neurophysiological advantage of bilingualism should be observed if and only if the control processes involved in the antisaccade task are shared between linguistic and motor domains. Else, no bilingualism advantage should be expected with the antisaccade task. Critically, we examined whether individuals using more than one language on a daily basis ('bilinguals') show a better performance in controlling irrelevant distracting information in a non-linguistic motor task, i.e. the antisaccade task, than individuals who use solely one language ('monolinguals'). To our knowledge, it is the first time that the neuronal underpinnings of oculomotor control processes and the time course of their activation were investigated in relation to language control. The paradigm chosen for the present study was a version of the antisaccade task in which the involvement of the processes of *conflict monitoring*, *response inhibition*, *vector inversion/movement initiation* as well as *switching* (task engagement and disengagement, attentional shifting) can be studied. Moreover, the role of the neuronal regions relevant for these control processes, mainly the anterior cingulate cortex (ACC) and the prefrontal cortex (PFC), as well as their interaction were examined in order to compare neuronal dynamics underlying control processes between the two groups.

1.2. The antisaccade task: control processes and neuroanatomical regions

The saccade task [49] is a task that allows for studying the voluntary control of action [50]. Participants are instructed to carry out either an automatic eye movement towards a visual target (prosaccade) or suppress this automatic eye movement and effectuate a saccade into the opposite direction (antisaccade), which depends on the color of the instructional cue preceding the target stimulus. Miyake and Friedman [51] classify the antisaccade task as a representative task to study *inhibition*, defined as the "deliberate overriding of dominant or prepotent responses"; more specifically the antisaccade task may require *response inhibition* [52]; for theoretical accounts claiming a separation between *response inhibition* and *interference suppression*, see [53,54]; see however [55]. Munoz and Everling [50] claimed that the antisaccade task does not only require response inhibition of the automatic prosaccade but also *vector inversion* (i.e. direction inversion), that is the stimulus vector must be inverted into the saccade vector in order to initiate a voluntary antisaccade (see also [56]). Furthermore, it has been suggested that *conflict monitoring* is also a relevant control process for successful antisaccade performance [57,58]. In general, conflict monitoring has been defined as the processes of monitoring for the occurrence of conflict in information processing and is on the evaluative side of cognitive control. In the antisaccade task, conflict monitoring is required because the requirement to look away from a visual stimulus creates a conflict between two opposing saccade commands, an automatic (sensory-driven) saccade toward the stimulus and a voluntary (internally driven) saccade away from the stimulus [59].

Conflict monitoring serves to translate the occurrence of conflict into compensatory adjustments in control, i.e. the conflict monitoring system evaluates the levels of conflict and communicates this information to systems responsible for control implementation [57]. In addition to *response inhibition*, *vector inversion* and *conflict monitoring*, control adjustment is also required in the transition between trials of different conditions, i.e. *switching*-related control processes, in the antisaccade task. In linguistic and non-linguistic tasks, the ability to *switch* between different task-sets reflects the flexibility and ease of transitioning to new task-set representations [51]. The switching process involves task disengagement, task engagement, suppression of previous task sets [20,60,61], overcoming of inhibition and attentional shifting [62]. When the direction of switch is from a more difficult towards an easier task, previously applied sustained inhibition needs to be overcome, which is not the case in switching from the easier to the more difficult task, producing the robustly observed asymmetrical switching cost [62]; for a review and alternative accounts to explain asymmetrical switching costs, see [61].

At the neuroanatomical level, the suppression and/or generation of saccadic eye movements involves activation in a number of cortical and subcortical structures, i.e. the dorsolateral prefrontal cortex (PFC), the anterior cingulate cortex (ACC), the lateral intraparietal area (LIP), the supplementary eye fields (SEF), the frontal eye fields (FEF), the superior colliculus (SC), the substantia nigra pars reticulata (SNpr) [50], the striatum [59,63] and the thalamus; for reviews, see [50,63,64]. During antisaccades, the automatic activation of saccade neurons contralateral to the visual target needs to be inhibited while saccadic activity ipsilateral to the stimulus (contralateral to the target movement) is required. The *inhibition* of saccade neurons is thought to be carried out by fixation neurons and interneurons in the FEF and SC, which receive the information to do so probably from the PFC, the SEF, or the SNpr.

The neuronal underpinnings of *vector inversion*, which is required for carrying out correct antisaccades beside *response inhibition*, are not yet very well understood but there is evidence that the LIP – which is at the interface between sensory and motor processing – and the FEF play a role in this process. Moreover, the anterior cingulate cortex (ACC) has been found to play a role in reflexive saccade suppression [64,65] and is thought to be active during *conflict monitoring* processes involved in antisaccade trials [57,64,66,67]. Once a pro- or antisaccade is initiated, fixation neurons in the FEF and SC cease to fire and there is a buildup of activity in saccade neurons. Control-related ERPs and oscillatory activity in the antisaccade task, thought to reflect *conflict monitoring*, *response inhibition*, *vector inversion/motor planning* and *switching*, will be presented as follows and the ERP markers are schematized in Figure 1.

Figure 1. ERP components. Overview of the different ERP components reported in the preparation, implementation and execution phases of saccadic eye movements in (A) cue-locked, (B) target-locked and (C) saccade-locked epochs. PSP: presaccadic positivity; LPP: late parietal positivity; A: antisaccade; P: prosaccade.

1.3. ERP and oscillatory markers of control processes in an antisaccade task

The above-mentioned control processes in an antisaccade task are associated with distinct ERP and oscillatory markers. For presenting these processes and their associated neurophysiological markers, we decided to follow their hypothesized chronological order: (1) *conflict monitoring*, (2) *response inhibition*, (3) *vector inversion/motor planning* and lastly, however concerning the transition between trials: (4) *switching*-related processes. Moreover, for each component, the phase in which it occurs, i.e. the ‘preparation’ (cue-locked), ‘implementation’ (target-locked) and ‘execution’ (saccade-locked), will be indicated. *Conflict monitoring* has previously been ascribed to a stimulus-locked fronto-central N2 component that is larger in the condition requiring control (i.e. antisaccade or nogo condition) as compared to a control condition (i.e. prosaccade or go condition; [68–70]; for a different view on the N2 in the antisaccade task, see [62]). The process of *response inhibition* of the automatic prosaccade in an antisaccade task is thought to be reflected by a target-locked parietal positivity at around 300 ms post-target onset (P3) which was shown to be reduced in anti- compared to prosaccades [62]. Although such a reduction of the P3 amplitude for a task involving inhibition can sound counterintuitive, however, it makes sense when, as it was suggested, the P3 modulation may reflect the decision to withhold a response [71]. Reduced P3 amplitudes have also been observed in the Eriksen Flanker task [72], the go/no-go task [71], or in a partially incongruent categorization task [73] and the processes underlying the reduction of the P3 amplitude may not be located in one single neuronal generator but may consist of a combination of the activity in inhibitory control regions and/or the outcome of high-level inhibitory control at target sites, e.g. the motor cortex [69]. Given that the increased N2 and reduced P3 frequently occur together they are frequently also considered as an 'N2/P3 complex' [62,74,75]. Another inhibitory component, but occurring during the preparation stage, is the frontal cue-locked positivity around 200 ms post-cue onset that is smaller in anti- than prosaccades [62] which probably reflects preparatory processes for the decision to withhold an automatic response. A third component that has been suggested to reflect inhibitory processes occurs during the saccade execution stage, i.e. a saccade-locked central presaccadic positivity (PSP) over a period of 250-50 ms prior to saccade onset that is smaller before anti- than prosaccades [76]. *Vector inversion and motor planning* have been found to be reflected by a fronto-central and occipital power decrease in the beta band (13-26 Hz) [77,78]. As for *switching*-related components, a target-locked late parietal positivity (LPP) for switch vs repetition trials at approximately 500-600 ms has been found to be larger for switch as compared to repetition trials, for both antisaccades and prosaccades, and is thought to reflect attentional shifting to the relevant task [62].

1.4. The present study

At present, there is behavioral and neuroimaging evidence in the literature that multiple language use involves domain-general control mechanisms which are also involved in non-linguistic control. Different evidence, however, gives support to hybrid accounts postulating that there are partially domain-general and partially language domain-specific control processes involved. The present study investigates the relation between language and oculomotricity and particularly asks whether bilinguals show a benefit in realizing a motor task involving control. The contribution of our study is to examine the neurodynamics of different control processes and subprocesses involved in an antisaccade task at the preparation (cue-locked), implementation (target-locked) and execution (saccade-locked) stages. EEG is a technique that allows to track phases of neuronal activation on a temporally fine-grained scale and therefore is a particularly useful technique for disentangling activity associated with different neurocognitive control processes and subprocesses. This should allow us to disentangle the processes for which an impact of bilingualism can occur. Moreover, source localization analyses will enable to identify neuronal generators associated with EEG markers thought to reflect these processes. Finally, by conducting DCM (dynamic causal modelling) analyses we aim at identifying effective connectivity dynamics at the network level between these neuronal regions. Effective connectivity concerns how activity in one brain region influences activity in another region [79]. In the present study, the investigation of effective connectivity will allow for learning more about the interplay of ACC and PFC in conflict monitoring and response inhibition processes in bilinguals and monolinguals.

In the present study, we aim to test if an impact of bilingualism on control performance can be observed in non-verbal oculomotor task. If control processes that are supposed to be involved in and trained by multiple language use show higher efficiency in a non-linguistic task, this can be considered as evidence in favor of accounts claiming domain-generality of control processes. If however, a more mitigated picture emerges, with only some processes being influenced by bilingualism while others are not, this can be taken as evidence supporting hybrid accounts claiming partially domain-general and partially domain-specific processes to be involved in language control. Moreover, in the present study, we aimed at investigating the predictive power of, e.g. second language proficiency, immersion experience, frequency of second language use, and frequency of language switching, on eye movement control capacity. By doing so, we aimed at giving a more fine-grained account of the multifaceted nature of bilingualism than it has been previously done.

For behavioral measures we expect to find longer saccade latencies and higher error rates for antisaccades than for prosaccades. Saccade latencies were measured as the duration from target onset until saccade onset and are given in milliseconds. As erroneous responses were considered expected saccade direction errors as well as saccade omissions (absence of saccade initiation) and are given as a percentage. Moreover, saccade latencies are predicted to be longer for switch compared to repetition trials. This switching effect is predicted to be larger for prosaccades than for antisaccades (AP > PP; > ; PA > AA). Both, the task effect ('Antisaccade effect') and the switching effect are expected to be larger for monolinguals than for bilinguals. At the neurophysiological level, a bilingual advantage for conflict monitoring should be reflected by a larger N2 effect size. This, advantage is expected to be modulated by the self-reported degree of control over and the frequency of daily language switching. A bilingual advantage for response inhibition should be reflected by smaller effect sizes of the cue-locked positivity, the P3 and PSP in bilinguals as compared to monolinguals. The processes of *vector inversion and motor planning* should be associated with a target-locked fronto-central and occipital beta (13-26Hz) power decrease in anti- compared to prosaccades. Finally, higher switching capacity should be reflected by smaller LPP effect sizes in bilinguals, reinforced in bilingual individuals with better controlled and more frequent daily language switching.

2. Methods

Approval for the study was given by the local Ethics Committee (*Conseil d'évaluation éthique pour les recherches en santé* at Paris Descartes – Sorbonne Paris Cité University) and the participants gave their informed written consent prior to participating in the study.

2.1. Participants

Forty right-handed participants (Edinburgh Handedness Inventory) were recruited. By their own account, participants had no history of current or past neurological or psychiatric diseases, they had normal or corrected-to-normal vision and normal color vision. Twenty of the participants were native speakers of French (L1) and highly proficient second language speakers of German (L2). One bilingual participant was excluded from the analyses due to a high degree of motor artifact contamination of the recorded EEG. The second group of 20 participants were native speakers of French (L1) with reduced use of other languages than their mother tongue (Frequency of daily non-native language use: 1.4 ± 1.2%). All participants were selected after having completed a language history questionnaire. Data on linguistic and environmental background measures can be found in Table 1. The average age did not differ between bilinguals (n = 19; 12 females, 7 males; 22.5 ± 2.6 years, range 19 –

30) and monolinguals ($n = 20$; 10 females, 10 males; 23.8 ± 5.1 years, range 19 – 37; $F < 1$). Bilinguals were late learners of German who studied the language at secondary school in France as their first non-native language (L2; Age of acquisition (AoA): 10.4 ± 0.8 years). They all had a regular use of their L2 (L2 daily frequency of use: 21.2 ± 16.9%) and 84% of the bilingual participants (16 individuals) also frequently used an additional L3 (L3 daily frequency of use: 6.5 ± 6.4%). The bilinguals' self-reported proficiency of 1.3 ± 0.6 [scale: 1: good – 5: poor] was high, which was also confirmed by the percentage of correct responses on a standardized test of German as a foreign language (*DAF – Deutsch als Fremdsprache*): 84.1 ± 7.4%.

Table 1. Background data. Linguistic and environmental background measures as assessed by a questionnaire are reported in the table. The mean and standard deviation (SD) is indicated for each category. AoA: Age of acquisition; Vid/Comp games: Video and Computer games.

	Bilinguals		**Monolinguals**		***p***
	(*n* = 19)		**(*n* = 20)**		
	Mean	**(SD)**	**Mean**	**(SD)**	
Age [years]	22.5	(2.6)	23.8	(5.1)	Ns
Self-rated proficiency L2 [1: good - 5: poor]	1.3	(0.6)	2.7	(1.1)	< .001
Self-rated proficiency L3 [1: good - 5: poor]	2.1	(1.0)	3.8	(0.9)	< .001
Frequency of L1 use [%]	71.0	(21.6)	98.6	(1.2)	< .001
Frequency of L2 use [%]	21.2	(16.9)	1.3	(1.2)	< .001
Frequency of L3 use [%]	6.5	(6.4)	0.0	(0.2)	< .001
AoA L2 [years]	10.4	(0.8)	--	--	--
Immersion in L2 environment [years]	1.4	(0.9)	--	--	--
Age of immersion [years]	18.8	(2.8)	--	--	--
Distance of immersion [years]	2.1	(2.5)	--	--	--
L2 proficiency: Grammar [%]	93.3	(4.8)	--	--	--
L2 proficiency: Communication [%]	92.7	(5.2)	--	--	--
L2 proficiency: Production [%]	66.3	(15.1)	--	--	--

L2 proficiency: Total [%]	84.1	(7.4)	--	--	--
Vid/Comp games [hour/week]	2.0	(4.8)	0.9	(1.4)	ns
Sport practice - high coordination [hour/week]	2.0	(3.1)	0.7	(1.2)	ns
Music practice [hour/week]	0.7	(1.6)	0.5	(0.9)	ns

2.2. Stimuli and Procedure

Stimuli were displayed on an Iiyama HM240DT monitor with a refresh rate of 160 Hz and a resolution of 800×600 pixels. The experimental sessions took place in a dimly lit room. Participants were seated 22 inches away from the screen and their head kept stable with a chin and forehead rest. Eye movements were recorded with an Eyelink® 1000 (SR Research, Ontario, Canada), with a temporal resolution of 1000 Hz, and a spatial resolution of 0.15°. Viewing was binocular but only movements of the right eye were monitored. Each session began with a 9 points calibration over the entire screen. Before each trial, central fixation was checked and compared to the calibration. If the distance between the fixation check and the calibration was greater than 0.75°, fixation was refused and the trial was reinitiated. When successful calibration was detected, the trial began. Online saccade detection corresponded to above-threshold velocity (30°/s) and acceleration (8000°/s^2).

Our experimental design was taken from the one use by Mueller et al. [62]. Each trial began with a blank screen, followed by a 1.5° x 1.5° black fixation cross presented in the center of the screen on a grey background. The combination of blank screen and fixation cross lasted 2100 ms with four different timings (1600+500 ms; 1400+700 ms; 1200+900 ms; 100+ 1100 ms respectively) randomized from trial to trial (see Figure 2), in order to avoid anticipation of cue onset. The fixation cross then turned into two different cues, a green or a red cross presented during 300 ms on the screen. The white target box (1.5° x 1.5°) then appeared on either the left or the right side of the screen, and was displayed for 700 ms on two possible eccentricities (6° and 10°) randomized across trials.

Figure 2. Timing of a prosaccade and an antisaccade trial.

Participants were instructed to make an eye movement towards the target box (prosaccade trial) if the cue was green, and an eye movement away from the target box, in a mirror symmetric location (antisaccade trial) when the cue was red. They were instructed to hold their fixation until the disappearance of the target box, and then, look back to the center of the screen. The experimental session (768 trials) was divided into three parts. In the first part of the experiment (pre), participants monitored a single task session of 96 prosaccade trials, and then 96 antisaccade trials (the order was counterbalanced across participants of each group). In the second part (mixed task session), they monitored 384 trials with pro- and antisaccade trials mixed. Then, in the third and last part (post) they monitored again a single task session of 96 prosaccade trials and a single task session of 96 antisaccade trials (in the same order than the first part). Before each task (prosaccades or antisaccades single task sessions or mixed task sessions), a block of training was proposed in order to familiarize the participants with the task. A short break was allowed to the participants between each block. All together (including single task and mixed task sessions), there was the same number of pro- and antisaccades (384). In the mixed task session, there were as many switches (defined as when the current saccade task differed from the task in the previous trial) as repetition trials (defined as when the previous saccade task was identical to the saccade task in the current trial). These diads, taking into account n-1 trials, were used in order to examine the switching-related processes in comparing prosaccades and antisaccades as a function of repetition and switching trials in the mixed task session. The second trial of a diad was considered as the target element for which the influence of the preceding trial was aimed to be studied. In total, 96 trials per diad type (PP, AP, AA, PA) were implemented over the total of 12 mixed blocks. To set up the lists of 32 diads per mixed block, we applied amongst others the constraint that the same type of saccade was presented no more than three times in a row. Each block started with two filler trials which were not included in the analysis.

2.3. Behavioral data analysis

Saccades with latencies below 50 ms were considered as early starts and removed from the analysis, as well as latencies above 500 ms, and trials containing eye blinks. Trials with latencies exceeding the threshold of mean ± 2 SD per condition were considered as outliers and hence excluded from the analysis. We averaged the saccade latencies for correct answers (*i.e.* correct saccade direction in regard to instructions) with data from both eccentricities (6° and 10°) and from both target locations (left and right). A trial was considered erroneous when the participant carried out a prosaccade if the instructional cue indicated an antisaccade trial (red cue), and if an antisaccade was carried out when the cue indicated a prosaccade (green cue). Error rates were averaged for both eccentricities and target locations.

For analysis of the behavioral measures (saccade latencies and error rate), a three-way repeated-measures ANOVA with Group as a between-subjects factor (monolingual vs. bilingual), and Saccade task (prosaccade vs. antisaccade) and Block type (mixed task blocks vs. single task blocks) as within-subjects factors was conducted. Planned comparisons were made to examine task effects for each Group. Moreover, a three-way repeated-measures ANOVA with Group as a between-subjects factor (monolingual vs. bilingual), and Saccade task (prosaccade vs. antisaccade) and Transition (switch vs. repetition) as within-subjects factors and saccade latencies as the dependent variable was performed to examine switching-related performance.

2.4. EEG acquisition and preprocessing

EEG preprocessing has been conducted using *Brain Vision Analyzer 2.1.0* (*Brain Products*). EEG was recorded from 32 channels mounted in an elastic cap (*ActiCap, Brain Products*) and recorded with the *Brain Vision Recorder, Brain Products*. All channels were referenced online against FCz. For data analysis, channels were re-referenced to an average reference. Electrode impedances were kept below 25 kΩ. Data were recorded at a sampling rate of 1000 Hz. An online band-pass filter of 0.01–100 Hz was used. Then, the data were filtered offline with a frequency band-pass of 0.05-100 Hz and a notch filter for 50 Hz was applied. On the continuous data, automatic artifact detection for non-ocular artifacts was conducted. Then, in order to remove artifacts from horizontal eye movements or from eye blinks from the continuous EEG signal, an ocular correction ICA (unbiased Infomax) was run using Fp1 as a VEOG channel and F7 and F8 as HEOG channels. For further analyses, only trials on which the participants carried out a correct oculomotor response and which were not contaminated by anticipatory eye movements (saccade latencies faster than 50 ms), saccade latencies of more than 500 ms (indicating that the participant did not correctly follow the instructions) or other movement artifacts, were included. The continuous EEG was segmented into epochs relative to three events: (1) cue-locked segments were segmented into epochs from 500 ms pre-cue until 1300 ms post-cue onset, (2) target-locked segments were segmented into epochs from 800 ms pre-target until 1000 ms post-target onset and (3) saccade-locked segments were segmented into epochs from 1100 ms pre-saccade until 700 ms post-saccade onset.

2.5. ERP analysis

ERP preprocessing and analyses have been conducted using *Brain Vision Analyzer 2.1.0* (*Brain Products*) and *EEGLAB* toolbox (version 13.2.2) [80] for MATLAB (version 7.12.0, R2011a). Event-related brain potentials (ERPs) were computed for each participant in each experimental condition for cue-, target- and saccade-locked epochs. Cue-locked segments were baseline corrected with the baseline set from 100 ms pre-cue onset until cue onset. Target-locked segments were baseline corrected with the baseline set from 400 ms to 300 ms pre-target onset (which is equivalent to the 100 ms baseline before cue onset). Saccade-locked segments were baseline corrected with a baseline set from 700 ms to 600 ms pre-saccade onset (which covers a time window that is on average before cue-onset). Then, in each experimental condition, the ERP activity was averaged over trials and over participants (i.e. grand average ERP). Statistical analyses of the ERP effects were performed for cue-, target- and saccade-locked ERPs in selected time windows based on previous studies and adjusted by visual inspection of the grand averages. All analyses were quantified using the multivariate approach to repeated measurement and followed a hierarchical analysis schema. In order to allow for an examination of hemispheric differences, the data recorded at the midline electrode sites were treated separately from the data recorded from lateral recording sites. Four-way repeated measure ANOVAs were conducted for the analyses for the lateral electrodes, including the within-subjects factors Saccade task (prosaccade vs. antisaccade) as well as two topographical variables Region (anterior vs. posterior) and Hemisphere (left vs. right) and the between-subjects factor Group (monolingual vs. bilingual). Four regions of interest (ROIs) resulting from a complete crossing of the Region and Hemisphere variables were defined: left anterior (F3, FC1, FC5), right anterior (F4, FC2, FC6), left posterior (CP5, CP1, P3), and right posterior (CP6, CP2, P4). The data from the midline electrodes were analyzed with a three-way repeated measure ANOVA including the within-subjects factors Saccade task (prosaccade vs. antisaccade) as well as Electrode (Fz, Cz, Pz) and the between-subjects factor Group (monolingual vs. bilingual). Note that for one bilingual and for one monolingual participant the Fz electrode provided noisy data and was consequently excluded from the analysis, which explains the reduced degrees of freedom in the analyses on midline electrodes. To investigate switching-related activity, separate analyses were conducted for antisaccades and prosaccades, respectively. Four-way repeated measure ANOVAs were conducted for the analyses on the lateral electrodes, including the within-subjects factors Transition (switch vs. repetition) as well as two topographical variables Region (anterior vs. posterior) and Hemisphere (left vs. right) and the between-subjects factor Group (monolingual vs. bilingual). Three-way repeated measure ANOVAs were conducted for the analysis of data from the midline electrodes, including the within-subjects factors Transition (switch vs. repetition) as well as Electrode (Fz, Cz, Pz) and the between-subjects factor Group (monolingual vs. bilingual). The dependent variable was the voltage amplitude [µV] averaged over the relevant interval of each ERP component of interest. The Greenhouse–Geisser correction [81] was applied when evaluating effects with more than one degree of freedom in the numerator. Post-hoc pairwise comparisons at single electrode sites were performed using a modified Bonferroni procedure [82]. A significance level of 0.05 was used for all statistical tests and only significant results are reported.

2.6. Dynamic causal modelling (DCM) analysis

The dynamic causal modelling (DCM) analysis was conducted in SPM12 (Wellcome Trust Centre for Neuroimaging, London, UK). DCM is a method that allows to test hypotheses of dynamics in a neuronal network which need to be defined as effective connectivity models.

Effective connectivity allows us to examine how activity in one brain region influences activity in another region [79]. The decision, which among different models best explains the data can then be carried out using Bayesian model selection. Here, based on (1) previous models of both saccade control [83] and the antisaccade task [50], as well as (2) fMRI evidence with an antisaccade task [84–86] and (3) TMS-MEG evidence of frontal top-down control on occipito-parietal excitability [87], two effective connectivity models were created (Figure 3) and tested for their validity and for effective connectivity differences between groups. Note that source reconstruction analyses for ERPs have sufficient precision only for cortical sources and consequently our modeling did not include any subcortical structures, despite their evident role in saccade control. Nine cortical sources, modeled as equivalent current dipoles (ECDs), were included in our effective connectivity models: left and right primary visual cortex (LV1, RV1), left and right lateral intraparietal area (LLIP, RLIP), anterior cingulate cortex (ACC), left and right prefrontal cortex (LPFC, RPFC), left and right frontal eye field (LFEF, RFEF). Table 2 presents the MNI coordinates and Figure 3C the locations of these cortical neuronal generators taken from two fMRI studies on an antisaccade paradigm, i.e. Ford [86] and Aichert, et al. [84], and transformed from Talairach to MNI space using the tal2mni tool (http://imaging.mrc-cbu.cam.ac.uk/imaging/MniTalairach). The source locations were specified while the dipole orientation parameters were left free and were individually adjusted during the model inversion process. During the model inversion process, DCM optimizes for each participant the information provided concerning the electromagnetic forward model and the neuronal sources (i.e. the number, locations and connections of the neuronal sources), aiming at minimizing free energy [88]. As forward model for the ERP data of the present study, the boundary element model (BEM) implemented in SPM12 was used. DCM models were designed as follows: Given that our paradigm involved visual stimulation, the left and right primary visual cortex were defined as input regions. The time window used for model adjustment started with cue-onset and ended at 400 ms after target-onset and consequently modeled source activity underlying the cue-locked positivity, the N2, the P3 and the PSP effects. The visual stimulation by the presentation of the cue was modeled at starting at 0 ms of the time window and reaching the input region 64 ms after cue onset. The target onset was modeled at time point 300, reaching the input region 64 ms after target onset. The following DCM were modeled: The visual input (cue, target) entered bilaterally to the primary visual cortex (LV1/RV1), which are connected to ipsi- and contralateral lateral intraparietal areas (LLIP/RLIP), which again were connected to the anterior cingulate cortex (ACC) in the frontal lobe. The ACC was bilaterally connected to the prefrontal cortex (LPFC/RPFC), which again had connections to ipsi- and contralateral frontal eye fields (LFEF/RFEF). Lateral connections were assumed between the left and right V1, left and right LIP, left and right PFC and left and right FEF. All connections were reciprocal and connected with the ipsi- as well as the contralateral site. In both models, the connections that are hypothesized to be modulated by experimental condition (‘modulatory connections’), i.e. Saccade task (prosaccade vs. antisaccade), are those from ACC to PFC and backward from PFC to ACC, from PFC to FEF and backward from FEF to PFC and between ACC and LEF and backward from FEF to ACC. Moreover, in Model 2, also the backward connection from FEF to LIP was modeled to vary between antisaccades and prosaccades, representing a potential modulation of LIP excitability influenced by input from FEF. Model 1, modeling an invariant backward connection from FEF to LIP excludes any top-down (inhibitory) control on parietal and occipital visual processing areas and hence represents cognitive processing in the antisaccade task that strongly relies on reactive control, i.e. control processes in reaction to the target in the antisaccade task, involving conflict monitoring and subsequent inhibitory regulation of the motor output. In contrast, Model 2 also includes a variable backward connection from FEF to the parietal sensory-motor transformation area LIP and is hence thought to model proactive inhibitory control, i.e. inhibitory reduction of the excitability of visual processing based on the information delivered by the visual cue during antisaccade processing. Proactive (inhibitory) control designates the endogenous preparation of a response tendency. Proactive inhibitory control leads to a behavioral slowing which facilitates reactive inhibition in case it is needed. Proactive and reactive control processes involve the same neuronal control network and there is a dynamic interplay between these two types of control [63,89], i.e. increased proactive control reduces the activation for reactive control and vice versa [89].

Figure 3. Effective connectivity models tested in a DCM analysis and equivalent current dipole locations. A, B The neuronal sources in the models are connected with forward (black), backward (dark grey) or lateral (light grey) connections. Connections that are modelled to vary between experimental conditions are depicted with dotted lines. Two different models were tested using the same architecture but modelling different backward connectivity from FEF to LIP, being invariant in the two experimental conditions (Model 1, panel **A**) or being allowed to vary between the two experimental conditions (Model 2, panel **B**). Connections between LV and FEF as well as LIP and FEF also connect to the contralateral side but are depicted only for the ipsilateral side for the sake of clarity of the figure. **C** Locations of the equivalent current dipoles included in the two models are depicted in an MRI of a standard brain in MNI space. ACC, Anterior cingulate cortex; LFEF/RFEF, left and right frontal eye field; LLIP/RLIP, left and right lateral intraparietal area; LPFC/RPFC, left and right prefrontal cortex; LV1/RV1, left and right primary visual cortex.

Table 2. Coordinates of neuronal sources used in the DCM analysis. Source coordinates have been taken from *Ford [86] and $^{\Delta}$Aichert et al. [84] and were transformed from Talairach to MNI space using the tal2mni tool (http://imaging.mrc-cbu.cam.ac.uk/imaging/MniTalairach). Abbrev., Abbreviation; BA, Brodmann area; Coord., coordinates.

Brain region	**Abbrev.**	**BA**	**MNI coord.**			**Cognitive processes**
			x	*y*	*z*	
Left primary visual cortex	LV1	17	-14	-88	4^{Δ}	visual stimulus processing
Right primary visual cortex	RV1	17	14	-78	12^{Δ}	visual stimulus processing
Left lateral intraparietal area	LLIP	7	-18	-68	58^{Δ}	sensory-motor transformation
Right lateral intraparietal area	RLIP	7	14	-68	54^{Δ}	sensory-motor transformation
Anterior cingulate cortex	ACC	32	8	12	34*	cognitive control; attention, motor modulation, response selection
Left prefrontal cortex	LPFC	10	-26	41	29*	cognitive control
Right prefrontal cortex	RPFC	10	38	50	26^{Δ}	cognitive control
Left superior frontal gyrus (left frontal eye field)	LFEF	6	-24	-8	54^{Δ}	eye movement control, inhibition
Right medial frontal gyrus (right frontal eye field)	RFEF	6	34	-8	54^{Δ}	eye movement control, inhibition

After inversion of each of the models on each subject's data set, Bayesian model selection was conducted on the group level – overall as well as for each group separately – by choosing the model with the highest log-evidence, indicating the model that best explains the data ('winning' model) [88]. The log-evidence is a measure in Bayesian model comparison [90] that allows to select, among competing models, which model best explains the data [88].

A random-effects (RFX) procedure was adopted because it was aimed to test if participants of the two groups used different cognitive strategies – modelled through the two models - for realizing the antisaccade task. Moreover, the log-evidence for each of the two models was extracted for each participant and subsequently submitted to a two-way ANOVA with Model type (Model 1 vs. Model 2) as a within-subjects factor and Group (bilingual vs. monolingual) as a between-subjects factor [91]. Then the values of the effective connectivity change in each modulatory connection, i.e. connections between neuronal sources that were allowed to vary between prosaccades vs. antisaccades, were extracted for each participant. The value for each modulatory effective connection change was subsequently submitted to an independent samples t-test with Group as a between-subjects factor.

2.7. Correlation analyses with language background measures

Finally, the information on the individual language background of the bilingual participants in our study were put into relation with the experimental measures on which group differences were observed. Most of the language background parameters included in our language background questionnaire, e.g. language switching experience, immersion in L2 environment, L2 proficiency, motivation to improve L2 proficiency, and the frequency of cross-language intrusions, were addressed with more than one question or test in order to obtain a precise picture. Hence, in a first step, one principal component for each of the language background parameters of interest was extracted from the responses to the corresponding questions. The language background parameters and the corresponding questions in square brackets are presented as follows: Language switching experience [Frequency of daily switching (1) in general, (2) in professional activity, (3) at week-ends, (4) during leisure time - obtained in absolute numbers - and (5) automaticity of language switching - on a scale of 10 [10: highly automatic - 1: requiring a lot of control]], immersion in L2 environment [Duration of immersion [years], (2) age of immersion [years], and (3) distance since immersion [years]], L2 proficiency [Proficiency subtest performance in (1) Grammar [%], (2) Communication [%], and (3) Production [%], as well as (4) proficiency self-evaluation [1: good - 5: poor]], motivation to improve L2 proficiency [Frustration due to (1) lack of written comprehension [10: high - 1: low], and due to (2) lack of oral comprehension [10: high - 1: low], as well as (3) the aim of L1 accent avoidance [10: very important - 1: not important], and (4) the aim to gain automaticity in L2 [10: very important - 1: not important]], and finally the frequency of cross-language intrusions [Frequency of (1) lexical intrusions [10: in every sentence – 1: never] and (2) syntactic intrusions [10: in every sentence – 1: never]]. Moreover, the frequency of daily L2 use [%] was obtained from a single question. Correlations involving these six language background parameters, i.e. language switching experience, immersion in L2 environment, L2 proficiency, motivation to improve L2 proficiency, frequency of cross-language intrusions, and the frequency of daily L2 use [%] and the ERP effect sizes and DCM modulatory connections (exclusively those connecting from or to ACC and PFC) for which group differences had been found, were conducted for the bilingual group.

2.8. Time-frequency analysis / Event-related spectral perturbation (ERSP) analysis

Time-frequency analyses were performed using the EEGLAB toolbox (version 13.2.2) [80] for MATLAB (version 7.12.0, R2011a). The original sampling rate of 1000Hz was kept throughout the analyses. Event-related synchronization (ERS) and desynchronisation (ERD) was calculated for target- and saccade-locked segments in the mixed task blocks. ERS and ERD represent the relative power increase (ERS) or decrease (ERD) in a post-stimulus interval relative to a pre-stimulus baseline. A baseline of 500 ms was used for both stimulus-types in order to allow for at least to oscillatory cycles as a baseline reference even in the lowest frequency involved, i.e. 4 Hz. For target-locked segments from 800 ms to 300 ms pre-target onset (which is equivalent to the 500 ms baseline before cue onset) and for saccade-locked segments from 1100ms to 600 ms before saccade onset (which covers a time window that is on average before cue-onset) were chosen. For the frequencies from 4 to 40 Hz, the number of cycles for Morlet wavelets was set to 2 for the lowest frequency but was set to increase with increasing frequencies while allowing to the same degree for an adjustment of the time window (medium between FFT and wavelet analysis (FFT: keeping the time window constant for all frequencies; Wavelet: keeping the number of cycles constant for all frequencies). Statistical analyses conducted for the ERSP data consisted of parametric t-tests (False Discovery Rate; FDR) correction to correct for multiple comparisons) for simple and main effects of factors and Bootstrapping for testing for an interaction between factors were conducted. A significance level of 0.05 was used for all statistical tests and only significant results were reported. The analyses included the factors Saccade task (prosaccade vs. antisaccade) and Group (bilingual vs. monolingual).

3. Results

3.1. Behavioral results

Behavioral data are presented in Table 3.

Table 3. Behavioral data for single and mixed task sessions are presented. Error rates (ERR) are given in percentage [%] and saccade latencies (SL) in milliseconds [ms]. AA, Antisaccade repetition; AP, Prosaccade switch; PA, Antisaccade switch; PP, Prosaccade repetition; SD, Standard Deviation.

	Total		**Bilinguals**		**Monolinguals**	
	(*n* = 39)		**(*n* = 19)**		**(*n* = 20)**	
	Mean	**(SD)**	**Mean**	**(SD)**	**Mean**	**(SD)**
ERR Prosaccades (single) [%]	.92	(2.34)	.47	(.77)	1.35	(3.17)
ERR Antisaccades (single) [%]	13.59	(9.11)	13.47	(7.56)	13.70	(10.57)
ERR Prosaccades (mixed) [%]	1.38	(1.50)	1.47	(1.65)	1.30	(1.38)
ERR Antisaccades (mixed) [%]	27.90	(15.42)	25.95	(13.75)	29.75	(17.00)
SL Prosaccades (single) [ms]	277.44	(21.49)	279.21	(21.28)	275.75	(22.10)
SL Antisaccades (single) [ms]	354.44	(42.78)	360.95	(36.95)	348.25	(47.80)
SL Prosaccades (mixed) [ms]	279.31	(29.62)	282.68	(23.69)	276.10	(34.65)
SL Antisaccades (mixed) [ms]	337.64	(42.68)	343.79	(34.93)	331.80	(49.12)
SL PP [ms]	276.20	(25.78)	279.36	(22.59)	273.20	(28.75)
SL AP [ms]	288.19	(27.31)	295.78	(27.46)	280.97	(25.78)
SL AA [ms]	336.98	(44.52)	342.68	(34.61)	331.57	(52.58)
SL PA [ms]	340.32	(47.26)	347.78	(40.98)	333.23	(52.60)

3.1.1. Error rates

The three-way ANOVA on saccade latencies revealed a main effect of Saccade task ($F(1, 37) = 118.79$, MSE = 125.64, $p < .001$, $\eta^2_p = .763$), reflecting the higher error rates for antisaccades (20.7 ± 14.4 %) than prosaccades (1.1 ± 2.0 %). Moreover, there was a main effect of Block type ($F(1, 37) = 75.96$, MSE = 27.86, $p < .001$, $\eta^2_p = .672$), reflecting the higher error rates in mixed task blocks (14.6 ± 17.1 %) than single task blocks (7.3 ± 9.1 %). Finally, there was a Saccade task by Block type interaction ($F(1, 37) = 64.18$, MSE = 28.86, $p < .001$, $\eta^2_p = .634$) indicating that for antisaccades error rates were significantly higher in mixed task blocks (27.9 ± 15.4 %) than in single task blocks (13.6 ± 9.1 %; $p < .001$), while there was no difference for prosaccades (mixed task blocks: 1.4 ± 1.5 %; single task blocks: 0.9 ± 2.3 %; $p > .10$).

3.1.2. Saccade latencies

The three-way ANOVA on saccade latencies revealed a main effect of Saccade task ($F(1, 37) = 228.60$, MSE = 782.81, $p < .001$, $\eta^2_p = .861$) reflecting the longer latencies for antisaccades (346 ± 43 ms) than prosaccades (278 ± 26 ms). Moreover, there was a main effect of Block type ($F(1, 37) = 11.27$, MSE = 191.70, $p < .01$, $\eta^2_p = .234$), indicating in average longer latencies in single task blocks (316 ± 51 ms) than in mixed task blocks (308 ± 47 ms). Finally, there was a Saccade task by Block type interaction ($F(1, 37) = 27.33$, MSE = 124.91, $p < .001$, $\eta^2_p = .425$) revealing that on average saccade latencies for antisaccades were significantly longer in single task blocks (354 ± 43 ms) than in the mixed ones (338 ± 43 ms; $p < .001$), while there was no difference for the prosaccade latencies between the two blocks (single task blocks : 277 ± 21 ms; mixed task blocks: 279 ± 30 ms; $F < 1$).

The three-way ANOVA to investigate the factor Transition corresponding to the switching effect (i.e. influence of the transition between trial n-1 and trial n, switch vs. repetition) revealed a main effect of Saccade task ($F(1, 37) = 165.38$, MSE = 752.04, $p < .001$, $\eta^2_p = .817$) indicating that the averaged saccade latencies were longer for antisaccade (339 ± 45 ms) than for prosaccade (282 ± 27 ms) trials. Moreover, there was a main effect of Transition ($F(1, 37) = 25.98$, MSE = 89.90, $p < .001$, $\eta^2_p = .412$) reflecting the longer latencies in switch (314 ± 46 ms) compared to repetition (306 ± 47 ms) trials. Finally, there was Saccade task by Transition interaction ($F(1, 37) = 4.22$, MSE = 175.22, $p < .05$, $\eta^2_p =$

.102) indicating that the Transition effect was larger in prosaccades (d = 12 ms, *p* < .001) than antisaccades (d = 3 ms, *p* > .10).

3.2. ERP results

In the following, first the results of the mixed task blocks and subsequently those of the single task blocks will be presented. Table 4 and Table 5 display an overview of the statistics for lateral and midline electrodes for the two task blocks.

Table 4. Analyses of ERP data for the lateral electrodes. Cue-locked pos., Cue-locked positivity; LPP, Late parietal positivity; MSE, Mean squared error; PSP, Presaccadic positivity.

Source	**df**	**Cue-locked pos.**			**N2**			**P3**			**PSP**			**Source**	**df**	***LPP Antisaccades***			***LPP Prosaccades***		
		Cue 150-250			**Target 160-200**			**Target 200-400**			**Saccade -250 --50**					**Target 400-650**			**Target 400-550**		
		F	***p***	**MSE**	***F***	***p***	**MSE**	***F***	***p***	**MSE**	***F***	***p***	**MSE**			***F***	***p***	**MSE**	***F***	***p***	**MSE**
Mixed task blocks																					
Sacc	1,37	8.85	**	0.19	12.07	***	0.44	15.56	***	0.70	8.75	**	0.34	Tran	1,37	20.56	***	0.19	10.98	**	0.30
G	1,37	<1		-	<1		-	<1		-	1.18		-	G	1,37	2.01		-	<1		-
Sacc × G	1,37	4.37	*	0.19	<1		-	<1		-	1.90		-	Tran × G	1,37	<1		-	<1		-
Reg	1,37	22.17	***	4.70	5.73	*	16.75	30.91	***	19.34	11.87	***	6.51	Reg	1,37	36.67	***	10.75	54.84	***	12.80
Reg × G	1,37	<1		-	<1		-	<1		-	2.90		-	Reg × G	1,37	<1		-	<1		-
Hem	1,37	<1		-	9.32	**	2.90	<1		-	4.23	*	1.47	Hem	1,37	<1		-	3.76		-
Hem × G	1,37	<1		-	4.14	*	2.90	2.58		-	1.21		-	Hem × G	1,37	1.52		-	<1		-
Sacc × Reg	1,37	1.21		-	<1		-	16.57	***	0.81	9.87	**	0.72	Tran × Reg	1,37	<1		-	6.63	*	0.47
Sacc × Reg × G	1,37	<1		-	3.13		-	1.13		-	2.07		-	Tran × Reg × G	1,37	<1		-	1.04		-
Sacc × Hem	1,37	1.63		-	<1		-	<1		-	2.02		-	Tran × Hem	1,37	<1		-	<1		-
Sacc × Hem × G	1,37	<1		-	<1		-	2.60		-	<1		-	Tran × Hem × G	1,37	<1		-	2.12		-
Reg × Hem	1,37	<1		-	11.08	**	1.20	6.30	*	1.10	<1		-	Reg × Hem	1,37	2.45		-	3.64		-
Reg × Hem × G	1,37	<1		-	<1		-	<1		-	<1		-	Reg × Hem × G	1,37	<1		-	<1		-
Sacc × Reg × Hem	1,37	<1		-	6.40	*	0.21	<1		-	<1		-	Tran × Reg × Hem	1,37	3.05		-	6.51	*	0.13

Sacc × Reg × Hem × G	1,37	<1		-	<1		-	<1		-	<1		-	Tran × Reg × Hem × G	1,37	2.37		-	3.32		-
Single task blocks																					
Sacc	1,37	23.44	***	0.22	19.39	***	0.84	18.82	***	0.86	39.95	***	0.97								
G	1,37	<1		-	<1		-	<1		-	<1		-								
Sacc × G	1,37	1.43		-	<1		-	<1		-	1.59		-								
Reg	1,37	7.88	**	4.16	<1		-	28.92	***	15.15	7.09	*	3.50								
Reg × G	1,37	<1		-	<1		-	<1		-	2.04		-								
Hem	1,37	<1		-	16.95	***	1.35	<1		-	<1		-								
Hem × G	1,37	<1		-	5.09	*	1.35	<1		-	2.02		-								
Sacc × Reg	1,37	<1		-	5.75	*	0.82	9.92	**		6.35	*	0.70								
Sacc × Reg × G	1,37	1.59		-	<1		-	1.49		-	<1		-								
Sacc × Hem	1,37	<1		-	<1		-	<1		-	<1		-								
Sacc × Hem × G	1,37	1.76		-	<1		-	2.15		-	<1		-								
Reg × Hem	1,37	<1		-	7.71	**	0.91	3.42		-	<1		-								
Reg × Hem × G	1,37	1.13		-	<1		-	<1		-	<1		-								
Sacc × Reg × Hem	1,37	<1		-	<1		-	<1		-	<1		-								
Sacc × Reg × Hem × G	1,37	<1		-	<1		-	1.20		-	<1		-								

Note: Hem, Hemisphere; G, Group; Reg, Region; Sacc, Saccade task; Tran, Transition; * $p < .05$, ** $p < .01$, *** $p < .001$.

Table 5. Analyses of ERP data for the midline electrodes. Cue-locked pos., Cue-locked positivity; LPP, Late parietal positivity; MSE, Mean squared error; PSP, Presaccadic positivity.

Source	df	Cue-locked pos.			N2			P3			PSP			Source	df	*LPP Antisaccades*			*LPP Prosaccades*		
		Cue 150-250			Target 160-200			Target 200-400			Saccade -250 --50					Target 400-600			Target 400-500		
		F	*p*	MSE	*F*	*p*	MSE	*F*	*p*	MSE	*F*	*p*	MSE			*F*	*p*	MSE	*F*	*p*	MSE
Mixed task blocks																					
Sacc	1,35	7.66	**	0.55	16.97	***	1.71	30.43	***	2.61	25.94	***	0.95	Tran	1,35	20.18	***	0.87	7.84	**	1.16
G	1,35	<1		-				<1		-	1.41		-	G	1,35	<1		-	<1		-
Sacc × G	1,35	5.25	*	0.55	<1		-	<1		-	4.68	*	0.95	Tran × G	1,35	3.33		-	<1		-
Elec	2,70	18.81	***	4.95	22.29	***	19.67	46.92	***	23.91	18.99	***	7.87	Elec	2,70	34.39	***	15.16	45.17	***	17.33
Elec × G	2,70	<1		-	<1		-	1.06		-	3.78	*	7.87	Elec × G	2,70	<1		-	<1		-
Sacc × Elec	2,70	4.03	*	0.38	2.72		-	5.13	*	0.99	11.64	***	0.93	Tran × Elec	2,70	<1		-	1.71		-
Sacc × Elec × G	2,70	<1		-	6.73	**	1.35	4.60	*	0.99	5.66	*	0.93	Tran × Elec × G	2,70	2.43		-	<1		-
Single task blocks																					
Sacc	1,35	34.26	***	0.85	24.09	***	1.83	54.58	***	1.94	53.06	***	2.51								
G	1,35	1.27		-	<1		-	<1		-	<1		-								
Sacc × G	1,35	2.29		-	<1		-	1.75		-	3.25		-								
Elec	2,70	16.89	***	4.26	13.15	***	11.11	39.40	***	17.17	15.16	***	3.44								
Elec × G	2,70	<1		-	<1		-	<1		-	2.52		-								
Sacc × Elec	2,70	7.58	**	0.34	3.64	*	1.51	8.32	***	1.07	7.46	**	1.06								
Sacc × Elec × G	2,70	3.07		0.34	<1		-	3.03		-	2.91		-								

Note: Elec, Electrode; G, Group; Sacc, Saccade task; Tran, Transition; * $p < .05$, ** $p < .01$, *** $p < .001$.

3.2.1. Preparation phase (cue-locked)

3.2.1.1. Cue-locked positivity: Cue-locked 150-250 ms

The four-way ANOVA including the factors Saccade task, Region, Hemisphere and Group conducted on lateral electrodes revealed a main effect of Saccade task ($F(1, 37) = 8.85$, MSE = 0.193, $p < .01$, $\eta^2_p = .193$) reflecting a reduced positivity in the antisaccade compared to the prosaccade condition (Cue-locked positivity effect; Figure 4). Moreover, there was a significant Saccade task by Group interaction ($F(1, 37) = 4.37$, MSE = 0.193, $p < .05$, $\eta^2_p = .106$), reflecting that the cue-locked positivity effect was larger in the monolingual group ($p < .01$) than in the bilingual group ($F < 1$). The three-way ANOVA including the factors Saccade task, Electrode and Group conducted on midline electrodes revealed a Saccade task by Electrode interaction ($F(2, 70) = 4.03$, MSE = 0.38, $p < .05$, $\eta^2_p = .103$), indicating that the cue-locked positivity effect was significantly larger on the Cz compared to the Pz electrode ($p < .01$).

Figure 4. Cue- and target-locked ERPs in the mixed task session on the three midline electrodes. The left panel shows the main effect of Saccade task and the right panel the difference waves (antisaccades minus prosaccades) in the two groups. Grey bars mark the time windows used for investigating the cue-locked positivity effect, as well as the target locked N2 and P3 components.

3.2.2. Implementation phase (target-locked)

3.2.2.1. N2: target-locked 160-200 ms

The four-way ANOVA including the factors Saccade task, Region, Hemisphere and Group conducted on lateral electrodes revealed a main effect of Saccade task ($F(1, 37) = 12.07$, MSE = 0.440, $p < .001$, $\eta^2_p = .246$), reflecting a larger negativity in the antisaccade than in the prosaccade condition (N2 effect). For midline electrodes, the three-way ANOVA including the factors Saccade task, Electrode and Group revealed a significant Saccade task by Group by Electrode interaction ($F(2, 70) = 6.73$, MSE = 1.35, $p < .01$, $\eta^2_p = .161$; Figure 4). Post-hoc analyses revealed that the Saccade task by Group interaction, i.e. a larger N2 effect in the bilingual group ($p < .05$) compared to the monolingual group ($F < 1$), was significant at the Fz electrode ($F(1, 35) = 5.39$, MSE = 1.36, $p < .05$, $\eta^2_p = .133$). Moreover, the Saccade task by Group interaction was also significant at the Pz electrode ($F(1, 35) = 4.83$, MSE = 1.13, $p < .05$, $\eta^2_p = .121$), where the N2 effect was smaller in the bilingual group ($F < 1$) than in the monolingual group ($p < .05$). Given that the control-related N2 is characterized as having a fronto-central distribution [92], only the group differences for the N2 effect on the Fz electrode will be discussed subsequently.

3.2.2.2. P3: target-locked 200-400 ms

The four-way ANOVA with the factors Saccade task, Region, Hemisphere and Group run on lateral electrodes revealed a significant main effect of Saccade task ($F(1, 37) = 15.56$, MSE = 0.695, $p < .001$, $\eta^2_p = .296$) reflecting a reduced positivity in the antisaccade compared to the prosaccade condition (P3 effect). Moreover, there was a Saccade task by Region interaction ($F(1, 37) = 16.57$, MSE = 0.809, $p < .001$, $\eta^2_p = .309$), indicating that the P3 effect was only significant over the posterior region ($p < .001$) but not over the anterior one ($F < 1$). For the midline electrodes, the three-way ANOVA with the factors Saccade task, Electrode and Group showed a Saccade task by Group by Electrode interaction ($F(2, 70) = 4.60$, MSE = 0.99, $p < .05$, $\eta^2_p = .116$; Figure 4). However, the post-hoc analyses only revealed a marginal Saccade task by Group interaction, i.e. a descriptively smaller P3 effect in bilinguals ($F =$

24.42, $p < .001$) than in monolinguals ($F = 34.59$, $p < .001$) at the Pz electrode ($F(1, 35) = 2.70$, MSE = 0.75, $p = .109$, $\eta^2_p = .072$).

3.2.2.3. Late parietal positivity (LPP): target-locked; Antisaccades: 400-650 ms, Prosaccades: 400-550 ms

The LPP effect was tested in the two Saccade tasks separately and after visual inspection, the target-locked time window 400-650 ms was selected for antisaccades while in prosaccades, the time window 400-550 ms was selected. In antisaccades, the four-way ANOVA with the factors Transition, Region, Hemisphere and Group run on lateral electrodes revealed a main effect of Transition (switch vs. repetition; $F(1, 37) = 20.56$, MSE = 0.19, $p < .001$, $\eta^2_p = .357$), reflecting a larger LPP in the antisaccade switch condition (antisaccade trial preceded by a prosaccade trial) than in antisaccade repetition condition (antisaccade trial preceded by an antisaccade trial; Antisaccade LPP effect; Figure 5). For prosaccades, the four-way ANOVA with the factors Transition, Region, Hemisphere and Group run on lateral electrodes revealed a main effect of Transition (switch vs. repetition; $F(1, 37) = 10.98$, MSE = 0.30, $p < .01$, $\eta^2_p = .229$) reflecting a larger LPP in the prosaccade switch condition (prosaccade trial preceded by an antisaccade trial) than in the prosaccade repetition condition (prosaccade trial preceded by a prosaccade trial; Prosaccade LPP effect; Figure 5). Moreover, there was a Transition by Region interaction ($F(1, 37) = 6.63$, MSE = 0.47, $p < .05$, $\eta^2_p = .152$) indicating that the prosaccade LPP effect was larger over the anterior region ($p < .001$) than the posterior region ($F < 1$).

Figure 5. Target-locked ERPs for the Transition types switch and repetition on the three midline electrodes. The left panel shows the ERPs for antisaccade trials and the right panel the ERPs for prosaccade trials, collapsed over the two groups. The grey bar marks the time window used for investigating the LPP component.

3.2.3. Execution phase (saccade-locked)

3.2.3.1. Presaccadic positivity (PSP): saccade-locked -250 to -50 ms

The four-way ANOVA including the factors Saccade task, Region, Hemisphere and Group conducted on lateral electrodes revealed a main effect of Saccade task ($F(1, 37) = 8.75$, MSE = 0.335, $p < .01$, $\eta^2_p = .191$), reflecting a reduced PSP in the antisaccade compared to the prosaccade condition (PSP effect; Figure 6). Moreover, there was a Saccade task by Region interaction ($F(1, 37) = 9.87$, MSE = 0.718, $p < .01$, $\eta^2_p = .211$) indicating that the PSP effect was larger over the anterior region ($p < .001$) than the posterior one ($F < 1$). The three-way ANOVA including the factors Saccade task, Electrode and Group conducted on midline electrodes revealed a Saccade task by Group interaction ($F(1, 35) = 4.68$, MSE = 0.952, $p < .05$, $\eta^2_p = .118$), indicating that the PSP effect was larger in the monolingual ($p < .001$) than in the bilingual group ($p > .05$). Moreover, there was a Saccade task by Group by Electrode interaction ($F(2, 70) = 5.66$, MSE = 0.93, $p < .05$, $\eta^2_p = .139$). Post-hoc analyses revealed a larger PSP effect in monolinguals ($p < .001$) than in bilinguals ($p > .10$), but only at the Cz electrode ($F(1, 35) = 5.09$, MSE = 0.597, $p < .05$, $\eta^2_p = .127$).

Figure 6. Saccade-locked ERPs in the mixed task session on the three midline electrodes. The left panel shows the main effect of Saccade task and the right panel the difference waves (antisaccades minus prosaccades) in the two groups. The grey bar marks the time window used for investigating the presaccadic positivity (PSP) component.

3.2.4. Single task blocks

Moreover, analyses on the single task blocks were conducted because we were interested if a bilingual advantage would show to the same degree if the two saccade tasks were presented in separate blocks. The data and statistics for mixed and single task blocks are presented in Table 4 for lateral electrodes and Table 5 for midline electrodes. In the preparation phase, for the cue-locked positivity (cue-locked 150-250 ms), the four-way ANOVA with the factors Saccade task, Region, Hemisphere and Group conducted on lateral electrodes revealed a main effect of Saccade task ($F(1, 37) = 23.44$, MSE = 0.216, $p < .001$, $\eta^2_p = .388$) reflecting a reduced positivity in the antisaccade compared to the prosaccade condition (Cue-locked positivity effect). The three-way ANOVA with the factors Saccade task, Electrode and Group conducted on midline electrodes revealed a Saccade task by Electrode interaction ($F(2, 70) = 7.58$, MSE = 0.383, $p < .01$, $\eta^2_p = .178$), indicating that the cue-locked positivity effect was significantly larger on the Cz as compared to Fz and Pz electrodes ($ps < .001$). In the implementation phase, for the N2 (target-locked 160-200 ms), the four-way ANOVA with the factors Saccade task, Region, Hemisphere and Group conducted on lateral electrodes revealed a main effect of Saccade task ($F(1, 37) = 19.39$, MSE = 0.841, $p < .001$, $\eta^2_p = .344$), reflecting a larger negativity in the antisaccade than in the prosaccade condition (N2 effect). Moreover, there was a Saccade task by Region interaction ($F(1, 37) = 5.75$, MSE = 0.822, $p < .05$, $\eta^2_p =$

.135), indicating that the N2 effect was larger over the posterior region ($p < .01$) than the anterior one ($p > .10$). For the P3 (target locked 200-400 ms), the four-way ANOVA with the factors Saccade task, Region, Hemisphere and Group run on lateral electrodes showed a significant main effect of Saccade task ($F(1, 37) = 18.82$, MSE = 0.863, $p < .001$, $\eta^2_p = .337$), reflecting a reduced positivity in the antisaccade compared to the prosaccade condition (P3 effect). Moreover, there was a Saccade task by Region interaction ($F(1, 37) = 9.92$, MSE = 0.838, $p < .01$, $\eta^2_p = .211$), reflecting the larger P3 effect size over the posterior region ($p < .001$) than the anterior one ($p > .10$). In the execution phase, for the PSP (saccade-locked -250 to -50 ms prior to saccade onset), the four-way ANOVA with the factors Saccade task, Region, Hemisphere and Group run on lateral electrodes revealed a main effect of Saccade task ($F(1, 37) = 39.95$, MSE = 0.965, $p < .001$, $\eta^2_p = .519$) reflecting a reduced PSP in the antisaccade compared to the prosaccade condition (PSP effect). Moreover, there was a Saccade task by Region interaction ($F(1, 37) = 6.35$, MSE = 0.703, $p < .05$, $\eta^2_p = .146$) indicating that the PSP effect was larger over the anterior region ($F(1, 37) = 26.98$, $p < .001$) than the posterior one ($F(1, 37) = 21.81$, $p < .001$). Finally, neither a main effect of Group nor an interaction involving Group was found.

3.2.5. Correlation analyses between language background measures and ERP effect sizes

Correlation analyses between language background measures (language switching experience, immersion in L2 environment, L2 proficiency, motivation to improve L2 proficiency, frequency of cross-language intrusions, and frequency of daily L2 use) and the ERP effect sizes and electrode sites for which group differences had been found [Cue locked positivity effect (Cz), N2 effect (Fz), P3 effect (Pz), PSP effect (Cz)] were conducted. At the execution phase (saccade-locked), our correlation analyses showed a negative correlation between immersion in the L2 environment and PSP effect size on the Cz electrode ($r = -.550$, $p < .05$). This correlation indicates that the more L2 immersion experience the bilingual participants had, the smaller was their PSP effect size. Moreover, there was a negative correlation between L2 proficiency and PSP effect size on the Cz electrode ($r = -.742$, $p < .01$) indicating that higher L2 proficiency was related to a smaller PSP effect size.

3.3. Dynamic causal modelling (DCM)

3.3.1. Model selection

Two DCMs were constructed and inverted for each participant, i.e. during the model inversion process, DCM optimizes for each participant the information provided concerning the electromagnetic forward model and the neuronal sources, aiming at minimizing free energy [88]. The two DCMs were Model 1 with only forward modulatory connections - i.e. which were modelled to vary between the experimental conditions prosaccade vs. antisaccade - between anterior cingulate cortex (ACC), bilateral prefrontal cortex (PFC) and bilateral frontal eye fields (FEF), and Model 2 including a backward modulatory connection, which implemented proactive top-down control from the FEF on sensory-motor processing in the parietal cortex, i.e. the bilateral lateral intraparietal cortex (LIP). Figure 7 illustrates the model comparison based on the relative log-evidence - i.e. a measure in Bayesian model comparison [90] that allows to select, among competing models, which model best explains the data [88] - for each participant. A model with higher log-evidence as compared to other models is the model that best explains the data (the ‘winning’ model). The log-evidence was analyzed for each individual participant as well as collapsed over all participants as well as groupwise

(Figure 7). Investigating the goodness of fit by comparing the log-evidence between the two models for each participant, Model 1 is the 'winning' model, i.e. better explains the data as measured by the higher log-evidence than the respectively other model, in 22 participants (11 bilinguals, 11 monolinguals) while Model 2 is the winning model for 17 participants (8 bilinguals, 9 monolinguals). This finding indicates that each of the two models – involving top-down parietal cortex excitability modulation between antisaccades and prosaccades (Model 2) or not (Model 1) – best explained the cognitive processing in approximately half of the participants in each group (Figure 7). Moreover, a two-way ANOVA with log-evidence as the dependent variable and Model type (Model 1 vs. Model 2) as a within-subjects factor and Group (bilingual vs. monolingual) as a between-subjects factor revealed that there was no significant main effect of Model type ($F < 1$), Group ($F < 1$) or Model type by Group interaction ($F < 1$) indicating that the repartition of the goodness of fit of the two models was not significantly different between the two groups.

Figure 7. Bayesian model comparison of the two effective connectivity models tested in a DCM analysis. A The relative (compared to the respectively other model) log-evidence for each participant is depicted. For each participant, the model with the relatively higher log-evidence is the 'winning' model, i.e. the model which better explains the data. **B** Relative log-evidences added up over subjects are displayed collapsed over both groups as well as for bilinguals and monolinguals separately.

3.3.2. DCM parameter estimates for modulatory connections

Then, parameter estimates were extracted for each modulatory connection, i.e. connections that were modelled to vary between the experimental conditions prosaccade vs. antisaccade, and an independent samples t-test with Group as a between-subjects factor and the effective connectivity difference in antisaccades as compared to prosaccades for each modulatory connection was run. Effective connectivity concerns how activity in one brain region influences activity in another region [79]. Descriptive and inferential statistics are shown in Table 6. For the 22 participants with Model 1 as the winning model, the independent samples t-test on modulatory parameters revealed a group difference for the ACC to RPFC modulatory connection ($t(20) = -2.501$, $p < .05$), indicating that in bilinguals there was a more negative effective connectivity in ACC to RPFC (-.317 ± .362) in antisaccades compared to prosaccades, while this was not the case in monolinguals (.064 ± .352). Moreover, there was a significant group difference for the RPFC to LFEF modulatory connection ($t(20) = 2.480$, $p < .05$) reflecting that monolinguals showed a more negative effective connectivity in RPFC to LFEF (-.391 ± .436) in antisaccades compared to prosaccades, while this was not the case in bilinguals (.090 ± .475). For the 17 participants with Model 2 as the winning model, the test on modulatory parameters revealed a group difference for the RPFC to RFEF modulatory connection ($t(15) = 2.137$, $p < .05$) indicating that in monolinguals there was a more negative effective connectivity from RPFC to RFEF (-.369 ± .331) in antisaccades compared to prosaccades, while in bilinguals the RPFC to RFEF effective connectivity was more positive (.201 ± .722). Moreover, there was a significant group difference for the RFEF to LLIP effective connectivity ($t(15) = -2.157$, $p < .05$) reflecting that in bilinguals there was a more negative effective connectivity in RFEF to LLIP (-.260 ± .401) while in monolinguals it became slightly more positive (.122 ± .327).

Table 6. Dynamic causal modelling (DCM) modulatory parameter estimates. Dynamic causal modelling (DCM) modulatory parameter estimates are presented for bilingual and monolingual participants overall on the left and for those with Model 1 as the winning model in the middle and for those with Model 2 as the winning model on the right. Biling., Bilinguals; M, Mean; Monoling., Monolinguals; SD, Standard Deviation.

	Model 1 & 2						**Model 1**						**Model 2**					
	Biling. (*n* = 19)		**Monoling.** (*n* = 20)		*t*	*p*	**Biling.** (*n* = 11)		**Monoling.** (*n* = 11)		*t*	*p*	**Biling.** (*n* = 8)		**Monoling.** (*n* = 9)		*t*	*p*
	M	**(SD)**	**M**	**(SD)**			**M**	**(SD)**	**M**	**(SD)**			**M**	**(SD)**	**M**	**(SD)**		
ACC > LPFC	.06	(.44)	-.06	(.35)	.90	.375	.04	(.46)	-.07	(.35)	.63	.534	.08	(.46)	-.04	(.37)	.61	.549
ACC > RPFC	-.21	(.41)	.15	(.35)	-2.95	**.005**	-.32	(.36)	.06	(.35)	-2.50	**.021**	-.06	(.45)	.26	(.34)	-1.67	.116
LPFC > ACC	-.01	(.57)	-.14	(.35)	.88	.382	-.13	(.40)	-.20	(.33)	.43	.669	.16	(.75)	-.08	(.39)	.82	.424
RPFC > ACC	-.09	(.44)	-.04	(.47)	-.40	.695	-.02	(.48)	-.19	(.53)	.81	.426	-.20	(.40)	.16	(.29)	-2.09	.054
ACC > LFEF	-.00	(.49)	-.11	(.35)	.81	.425	-.06	(.33)	-.05	(.44)	-.09	.931	.08	(.66)	-.19	(.20)	1.11	.298
ACC > RFEF	.02	(.40)	-.04	(.43)	.44	.661	-.02	(.22)	.06	(.45)	-.49	.634	.08	(.58)	-.15	(.41)	.95	.359
LPFC > LFEF	.15	(.63)	-.03	(.31)	1.08	.292	.17	(.75)	.09	(.32)	.32	.751	.11	(.47)	-.17	(.24)	1.54	.154
LPFC > RFEF	-.13	(.51)	-.16	(.56)	.21	.838	-.19	(.62)	-.08	(.62)	-.40	.692	-.05	(.33)	-.26	(.49)	1.06	.305
RPFC > LFEF	-.09	(.51)	-.32	(.42)	1.53	.136	.09	(.48)	-.39	(.44)	2.48	**.022**	-.34	(.46)	-.23	(.41)	-.53	.605
RPFC > RFEF	.04	(.59)	-.17	(.37)	1.35	.185	-.08	(.46)	-.01	(.32)	-.41	.683	.20	(.72)	-.37	(.33)	2.14	**.049**
LFEF > LLIP	-	-	-	-	-	-	-	-	-	-	-	-	-.18	(.71)	.21	(.42)	-1.39	.184
LFEF > RLIP	-	-	-	-	-	-	-	-	-	-	-	-	.19	(.62)	-.15	(.59)	1.16	.264
RFEF > LLIP	-	-	-	-	-	-	-	-	-	-	-	-	-.26	(.40)	.12	(.33)	-2.16	**.048**
RFEF > RLIP	-	-	-	-	-	-	-	-	-	-	-	-	.12	(.56)	-.06	(.52)	.68	.507

Group difference *p* values uncorrected for multiple comparisons.

3.3.3. Correlation analyses between language background measures and DCM modulatory connections

Correlation analyses between language background measures and the DCM modulatory connections (exclusively those connecting from or to ACC and PFC) for which group differences had been found, were conducted for the bilingual group. There was a positive correlation between the motivation to improve L2 proficiency and the modulatory connection LPFC to LFEF (r = .550, p < .05), indicating that a higher motivation to improve L2 proficiency was associated with an increase in LPFC to LFEF effective connectivity in antisaccades compared to prosaccades.

3.4. Time-frequency results

In order to test for *vector inversion and motor planning,* we tested for target-locked fronto-central and occipital beta (13-26Hz) power changes in anti- compared to prosaccades. There was a significant ($p < .05$, FDR-corrected) power decrease in the antisaccade compared to the prosaccade condition around 150 ms after target onset in the beta band over the vertex and occipital scalp (Figure 8). There was no main effect of or interaction with Group.

Figure 8. Time-frequency analysis. A Event-related spectral perturbations (ERSPs) time-locked to target onset are plotted for the Cz electrode for antisaccades and prosaccades and a panel for significant ERSP differences between Saccade tasks is displayed on the right side. **B** The beta power decrease at around 150 ms after target onset in antisaccades compared to prosaccades over the central and posterior scalp is plotted at frequency 24 Hz. A panel showing the electrodes with a significant ERSP difference between Saccade tasks in red is plotted on the right side.

4. Discussion

In the present study, we investigated the neurodynamics of control processes involved in performing an antisaccade task in two groups differing in language use, i.e. bilinguals and monolinguals. The rationale was to examine whether executive control processes whose efficiency is reinforced by the frequent use of a second language can lead to a benefit in the control of eye movements, i.e. a non-linguistic activity. While the two groups performed similarly at the behavioral level, at the neuronal level clear differences emerged in the ERP measures and dynamic causal modelling (DCM) between bilinguals and monolinguals.

4.1. ERP data

In our study we found a larger target-locked N2 in the antisaccade than in the prosaccade condition -, assumed in the literature to reflect conflict monitoring. The observation of a larger target-locked N2 effect in bilinguals than in monolinguals suggests based on previous studies that this enhancement could be associated with stronger control [93]; for a review, see [92]. However, there is currently no unanimous view on the exact functional role of the variation of the N2 amplitude and/or effect size in terms of conflict monitoring capacity [94]. In addition, our ERP data also revealed a group effect for markers of inhibition. A smaller effect size was observed in bilinguals compared to monolinguals for the cue-locked positivity, the target-locked P3 and the saccade-locked presaccadic positivity (PSP), i.e. three ERP markers thought to reflect inhibitory processes / decision to withhold an automatic response. Moreover, in bilinguals, negative correlations were observed but only between the PSP effect size and (1) L2 proficiency and (2) immersion experience suggesting that these two linguistic factors are good indicators of inhibitory control improvement. Higher L2 proficiency and immersion experience may, due to the continuous need to control over the L1 and the increasingly automatic L2, lead to strengthened inhibitory control. Bilinguals with high compared to those with low second language proficiency have previously been shown to have a behavioral advantage in an oculomotor control task [42], an advantage that had however been attributed to improved performance monitoring rather than inhibitory control. Taken together, the increased N2 effect size in bilinguals, thought to reflect their more efficient conflict monitoring, combined with the reduced effect sizes on markers reflecting inhibitory control, i.e. cue-locked positivity, the target-locked P3 and the saccade-locked presaccadic positivity (PSP), may reflect a dynamic interplay between strengthened conflict monitoring leading to subsequently reduced cost for inhibitory control in realizing the task. Finally, no difference between groups was observed for the marker of switching-related activity, i.e. the target-locked late parietal positivity (LPP). That means that bilinguals and monolinguals performed similarly to change from one task to the other in both direction of switch. The type of bilinguals tested in the present study, i.e. late bilinguals immersed in their L1 environment who regularly use their L2, however without frequent switches between the two languages, may have an expertise in conflict monitoring and inhibitory control, but less so in switching-related processes. Hence, further investigation should try to clarify if different types of bilinguals with respect to their language-switching activity show different profiles of control enhancement. To sum up, we showed that bilinguals were more efficient for detecting conflict and for inhibitory control, whereas no group difference was observed for task switching.

4.2. DCM data

Our study of effective connectivity used two dynamic causal models (DCMs) of the executive control network supposed to be involved in eye movement control. Model 1 including only modulatory forward connections from the anterior cingulate cortex (ACC) to the prefrontal cortex (PFC) and to the frontal eye fields (FEF) explained the data in 22 participants, i.e. 11 bilinguals and 11 monolinguals. Model 2, which beyond the modulatory forward connections also included a modulatory backward connection implementing top-down control from FEF to the lateral intraparietal area (LIP) was the model best explaining the data in 17 participants, i.e. 8 bilinguals and 9 monolinguals. The equal repartition of the prevalence of the two models in the two groups indicates that there is no qualitative difference in cognitive control strategies used by the two groups. Note that for around half of the participants of each group, model 1 better explained the data and for the other half model 2, which suggests that individual differences may exist concerning the top-down regulation of excitability in the intraparietal cortex, thought to be responsible for sensory-motor transformations.

However, for parameter estimates of each modulatory connection differences between the two groups emerged. In DCM, the notion of causality is used in a control theory sense and means that activity in one brain area causes dynamics in another, and that these dynamics cause the observations [79]. In this sense, a positive effective connection indicates that the activity in the source region's neural population-level activity leads to an increase in the neural population-level activity in the target region, while a negative effective connection indicates that the activity in the source regions leads to a decrease of the activity in the target region. Positive effective connections are thought to reflect an excitatory effect from the source to the target region [95]. Negative effective connections have been interpreted to reflect, either a top-down inhibitory influence from the source to the target region [89,95], or an increase of the response threshold in the target region (leading to a decreased activation in the target region; [89]. Our main interest focused on the effective connections from the anterior cingulate cortex (ACC) – thought to be a core neuronal region involved in conflict monitoring – and the bilateral prefrontal cortex (PFC) – thought to be a crucial region involved in inhibitory control implementation. Group differences were found for the connection from ACC to RPFC, with a more negative effective connectivity in antisaccades compared to prosaccades in bilinguals but not in monolinguals. The more negative effective connectivity from ACC to PFC in bilinguals may reflect their strong reliance on highly efficient conflict monitoring in the ACC and its influence on the subsequent inhibitory control implementation in the PFC. The negative connection from ACC to PFC may reflect an inhibitory effect from ACC to PFC activity or in contrast an increase of the response threshold in the PFC, reflected by its reduced activity. The strong reliance on ACC guided conflict processing may produce reduced cost for the subsequent PFC based inhibitory control implementation and hence may reflect more efficient conflict monitoring. Moreover, this pattern of source activation may also be reflected on the ERP level, on which the increased N2 effect in bilinguals may reflect the stronger reliance on conflict monitoring, which might be causally related to the subsequently smaller effects on markers of inhibitory control, i.e. the cue-locked positivity, the target-locked P3 and the saccade-locked PSP effects. Moreover, there was a group difference for the effective connectivity from RPFC to LFEF and RFEF, with a more negative effective connectivity in antisaccades compared to prosaccades in monolinguals but not in bilinguals. The more negative effective connectivity in RPFC to RFEF and LFEF in monolinguals but not in bilinguals may reflect a stronger top-down inhibitory influence from PFC to FEF in monolinguals. Finally, there was a group difference in the modulatory backward connection from RFEF to LLIP, with a more negative effective connectivity in antisaccades compared to prosaccades in bilinguals but not in monolinguals. This more negative RFEF to LLIP effective connectivity may reflect a top-down inhibitory influence from FEF on parietal cortical excitability producing an increase of the response threshold in the LIP, which should be reflected at the neuronal level by a reduced activation of the LLIP.

The more negative effective connectivity from ACC to PFC in bilinguals may reflect a stronger reliance on ACC-directed control (stronger reliance on conflict monitoring) in bilinguals and the more negative effective connectivity from RPFC to both RFEF and LFEF in monolinguals may reflect a stronger reliance on PFC-directed control (stronger involvement of inhibitory control) in monolinguals in performing the antisaccade task. The finding of group differences on effective connectivity modulations between experimental conditions indicates that the two groups differentially rely more strongly on ACC-driven control vs PFC-driven control and that the automaticity of the top-down control processes conflict monitoring and inhibition differs between the two groups. Relating the modulatory effective connectivity strength to language background measures, it was found that the motivation to improve L2 proficiency was positively correlated with the modulatory connectivity between RPFC and LFEF indicating that the aim to improve proficiency is associated with top-down inhibitory control. Moreover, the more negative effective connectivity from RFEF to LLIP in bilinguals may reflect preparatory, proactive (i.e. endogenous preparation of a response tendency) top-down inhibitory control on the excitability in the intraparietal cortex, an area thought to be responsible for sensory-motor transformations. The information delivered by the preparatory cue may potentially be used more strongly by bilinguals for reducing the interference from the visual antisaccade target appearing on the side opposite to the intended saccade direction. This proactive inhibitory control may be beneficial for reducing the subsequent need for reactive inhibitory control, when the stimulus that needs to be inhibited appears at the screen. Proactive and reactive control processes have been shown to involve the same neuronal control network and there is a dynamic interplay between these two types of control [63,89], in that increased proactive control reduces the activation for reactive control and vice versa [89].

To sum up, in bilinguals, the negative effective connectivity from ACC to PFC and from FEF to LIP may indicate a preference in tackling the conflict in an antisaccade task via conflict monitoring as well as via cue-dependent preparatory, proactive downregulation of parietal sensory-motor transformation. This may hence lead to less costly reactive and inhibitory control implementation, while in monolinguals, the negative effective connectivity from PFC to FEF may indicate that monolinguals preferentially tackle the antisaccade conflict by PFC-based inhibitory control. A key conclusion from the present study is that the investigation of control processes and their neural substrate in isolation might not reveal the most accurate picture but that they should always be considered within their tight interrelation with other control processes. Further investigation should also take into consideration the role of subcortical structures in cognitive and motor control, given their involvement in the antisaccade task [50] as well as in multiple language control [96–98], for which neuroimaging techniques such as fMRI or NIRS could provide useful information. Moreover, different profiles of bilinguals may show different patterns of control use, hence the study of bilinguals showing a high degree of language switching or mixing as well as bilinguals in early stages of immersion experience may provide further insight on the patterns of neuroplastic control adaptations.

4.3. Domain-general control in multiple language use

The present findings support psycholinguistic theories postulating domain-general control involvement in multiple language control. The sustained coactivation of a bilingual's languages [8–12] and the bidirectional cross-language influences [13–15] require efficient top-down control in order to allow for adaptation to speakers of one of the two – or both - languages and for fluid communication. Due to frequent situations of language interference and conflict, bilinguals may in the long run develop more efficient conflict monitoring and inhibitory control in order to prevent and resolve situations of conflict. The observation that ERP and effective connectivity differences between bilinguals and monolinguals are observed in a completely non-linguistic task, i.e. the antisaccade task, is strong evidence that the control processes recruited by bilinguals to control the use of their languages are domain-general and hence shared between different cognitive domains.

4.4. Time-frequency data

In order to test for *vector inversion and motor planning,* we tested for target-locked fronto-central and occipital beta (13-26Hz) power changes in anti- compared to prosaccades. There was a significant power decrease in the antisaccade compared to the prosaccade condition around 150 ms after target onset in the beta band over centro-posterior scalp but there was no main effect of or interaction with Group. Note that this effect occurred before saccade onset in prosaccades (279 ± 30 ms) and antisaccades (338 ± 43 ms) and is hence not linked to the muscular activity during motor execution itself. For the change of a motor program, power modulations in the alpha (8-12 Hz) and beta (13-26 Hz) frequency bands have been shown to be of relevance. Alpha and beta oscillations play a role in holding a status quo and for inhibiting movements. Alpha oscillations have been suggested to play a role in the suppression of the excitability in sensory and motor areas, e.g. regulating the receptiveness/readiness in saccadic control network circuits, and to serve a top-down control function for suppressing externally driven saccades in favor of internal goals [99]. Beta oscillations are important for the maintenance of a current motor state, and beta power highest during holding periods after movements [78]. Beta attenuation however occurs during voluntary movements as well as during preparation and execution of movements, where beta activity is replaced by faster rhythms in the gamma-band (30-100 Hz) [78]. Cordones et al. [77] found stronger fronto-central and occipital beta power decreases in antisaccades compared to nogo trials during the instructive period, which may indicate that these beta power variations do not reflect inhibitory processes but motor planning and preparation. Moreover, beta power decreases have been found in the somatosensory cortex contralateral to the stimulus in an antisaccade task, which has been claimed to reflect somatosensory gating, i.e. increasing the excitability of the cortical region that shows a beta decrease [100]. To sum up, power variations in the beta band seem to reflect processes of vector inversion and motor planning in the antisaccade task, but these control processes do not seem to differ between bilinguals and monolinguals.

4.5. Conclusion

In the present neurophysiological study examining the impact of bilingualism on event-related potentials (ERP), event-related spectral perturbation (ERSP) and the effective connectivity of the underlying neuronal generators (dynamic causal modelling; DCM) in a non-linguistic motor task, we provide evidence for the crucial role of domain-general control involvement in the control over multiple language use. Bilinguals compared to monolinguals show an increased neurophysiological effect for conflict monitoring and reduced neurophysiological effect sizes on markers of inhibitory control. Moreover, there is evidence from dynamic causal modelling that bilinguals rely more strongly on ACC-driven control and monolinguals on PFC-driven control. Finally, L2 proficiency, motivation to improve L2 proficiency and immersion experience appear to be good predictors of a more efficient inhibitory control.

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Figure 1

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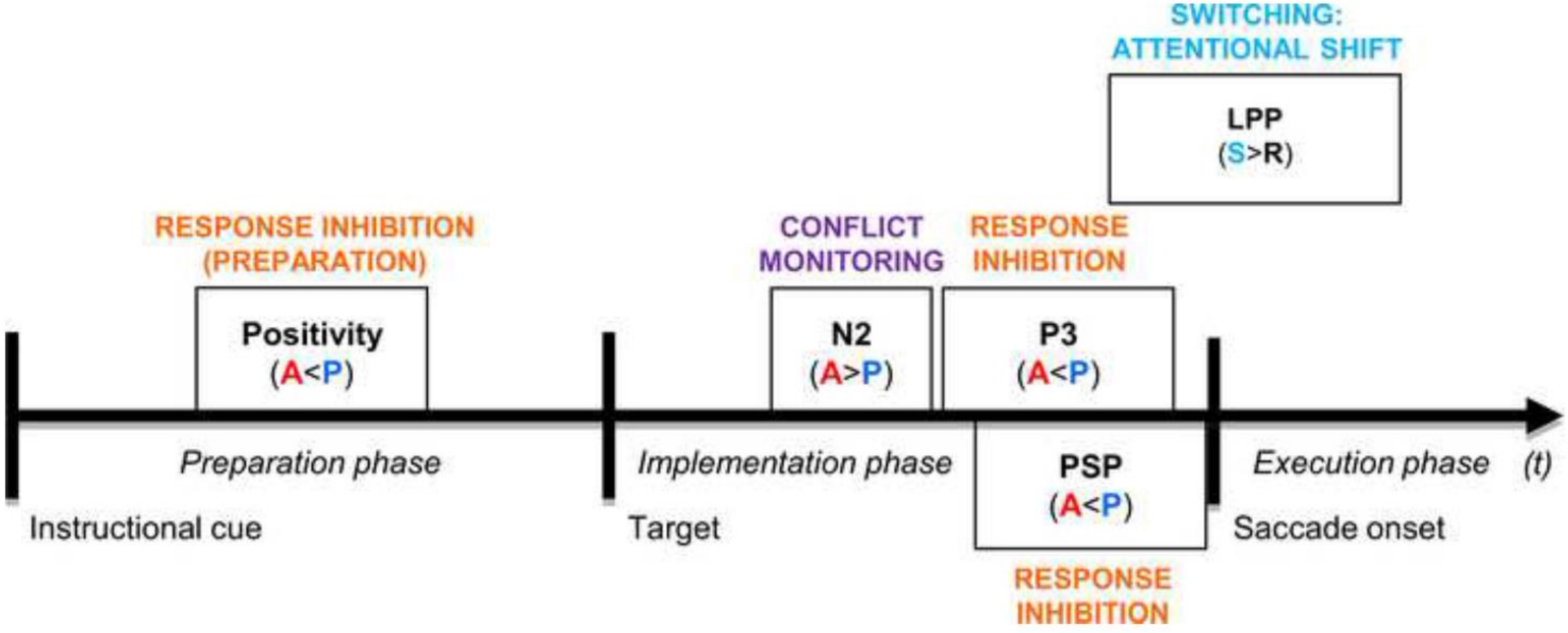
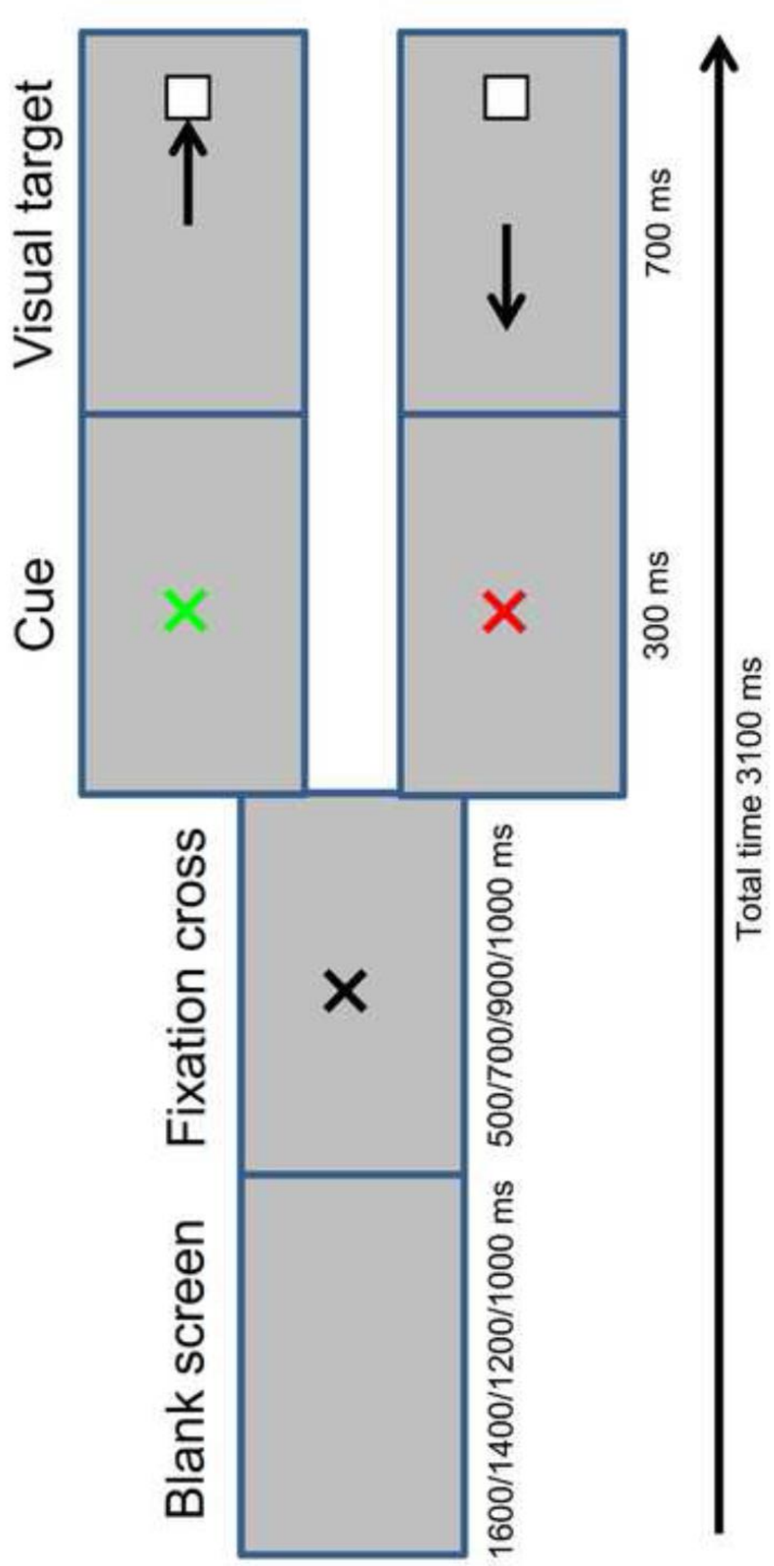


Figure 2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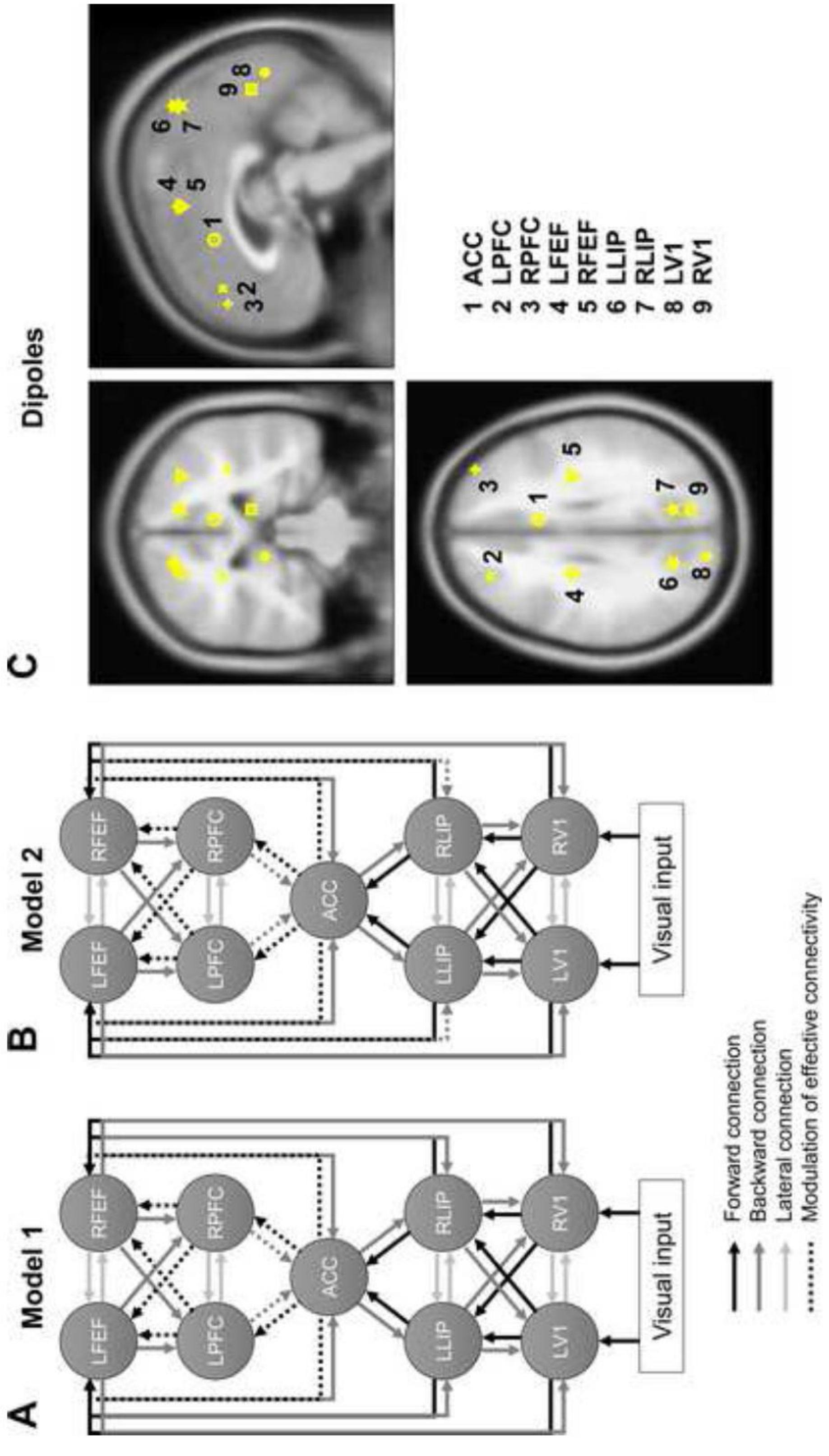

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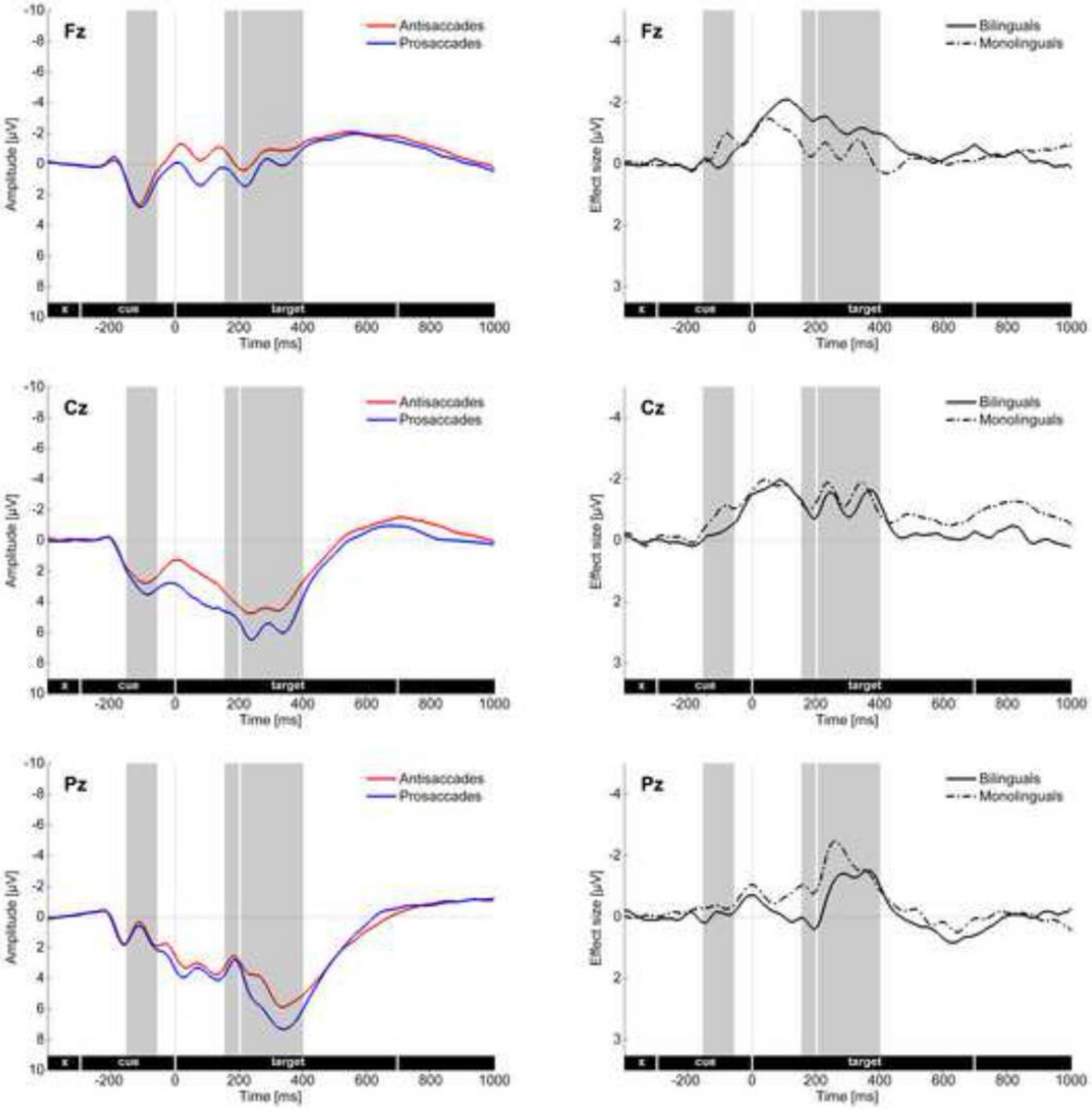

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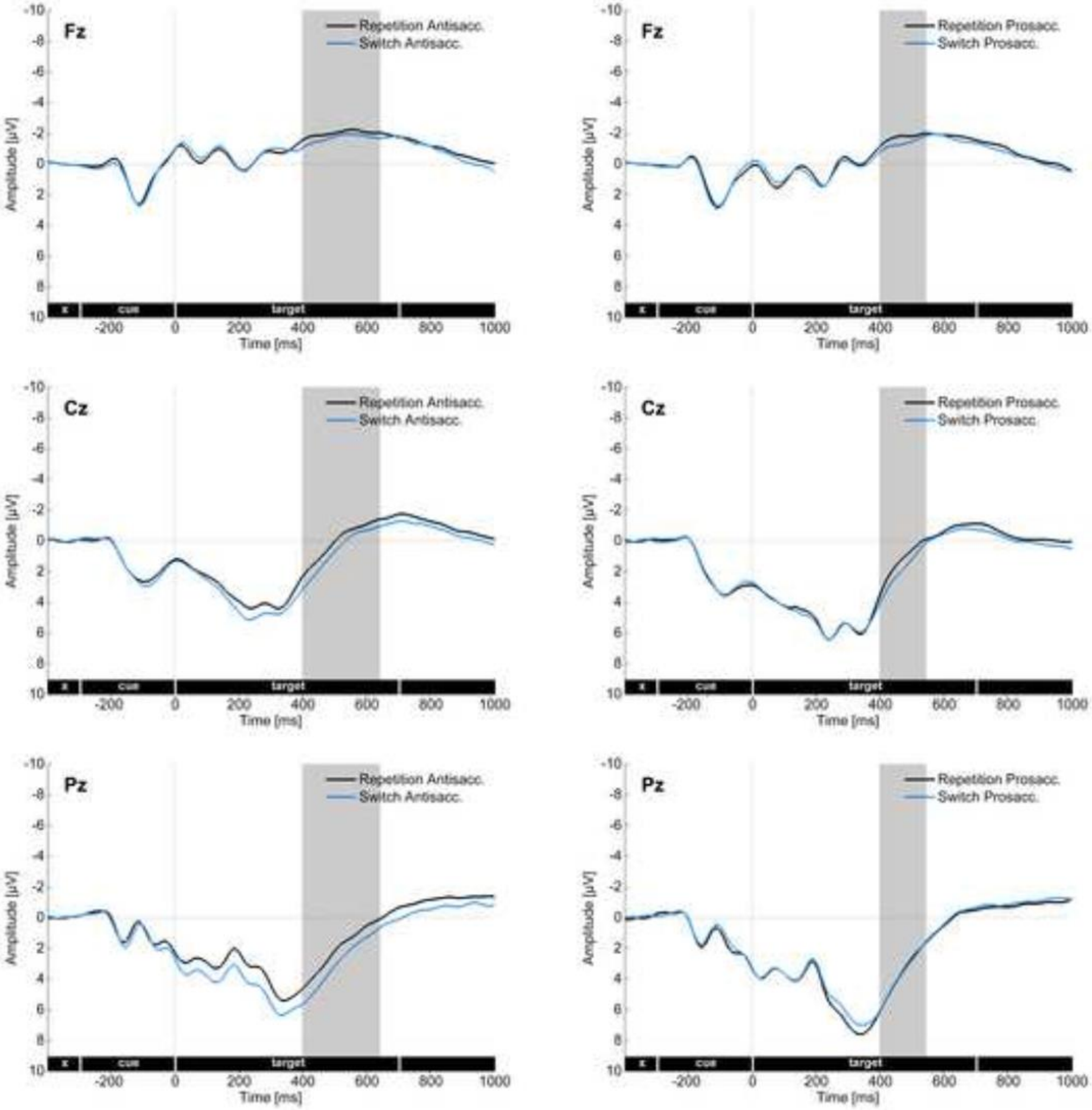

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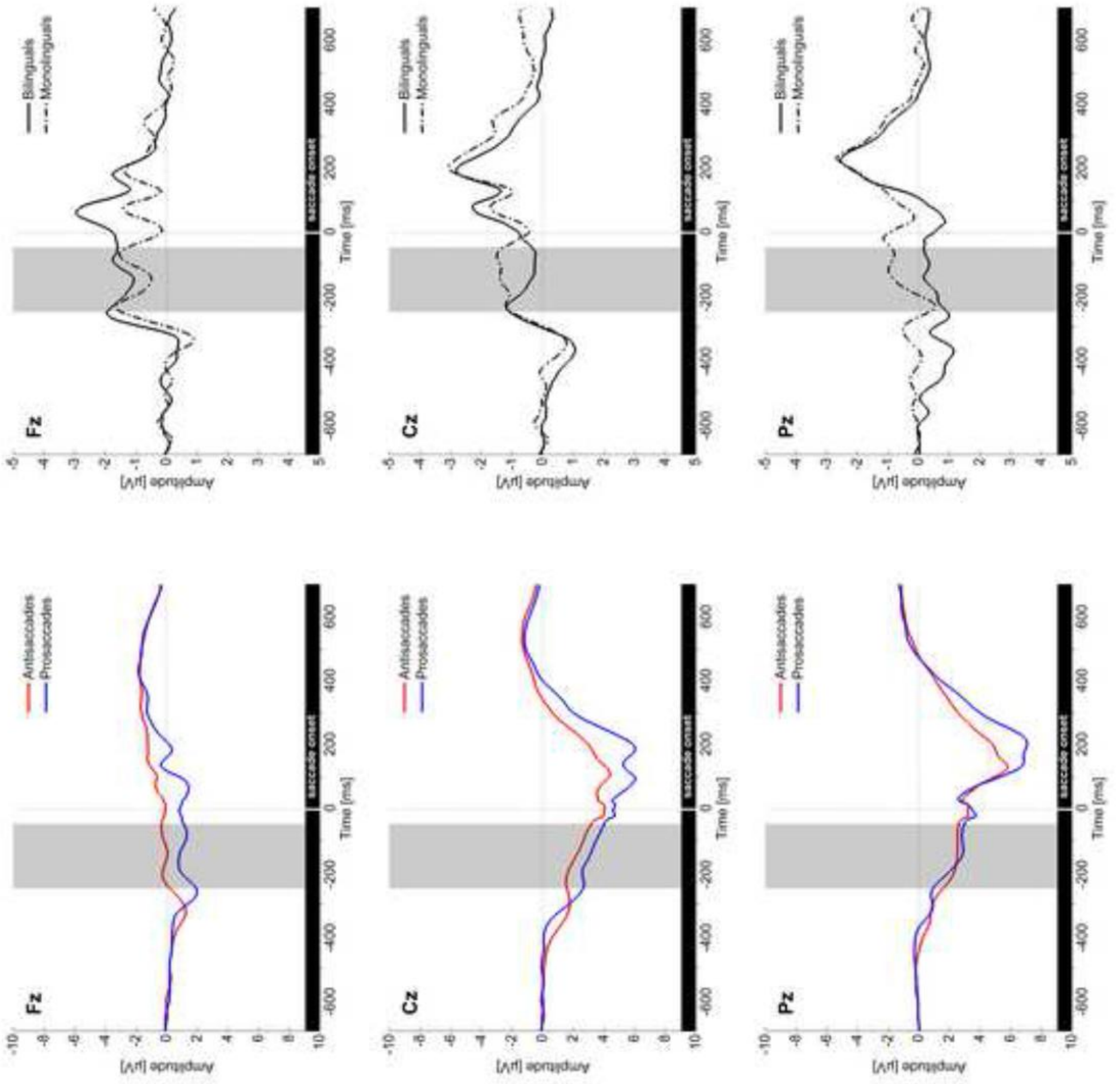

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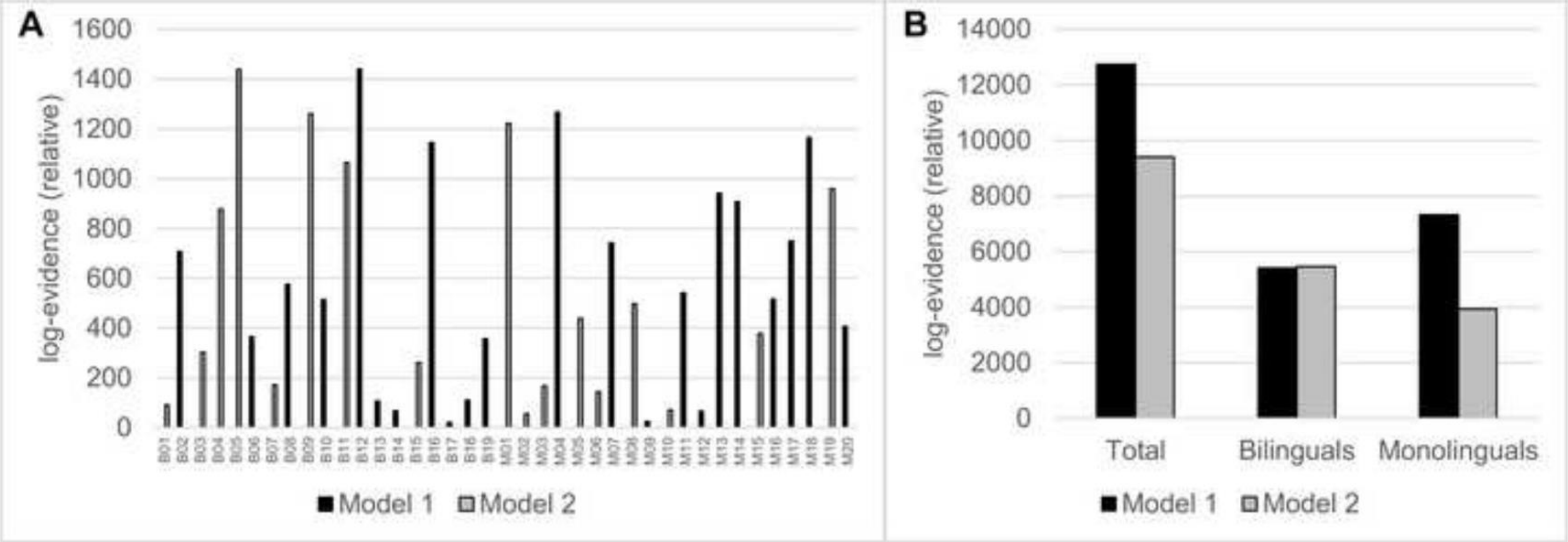

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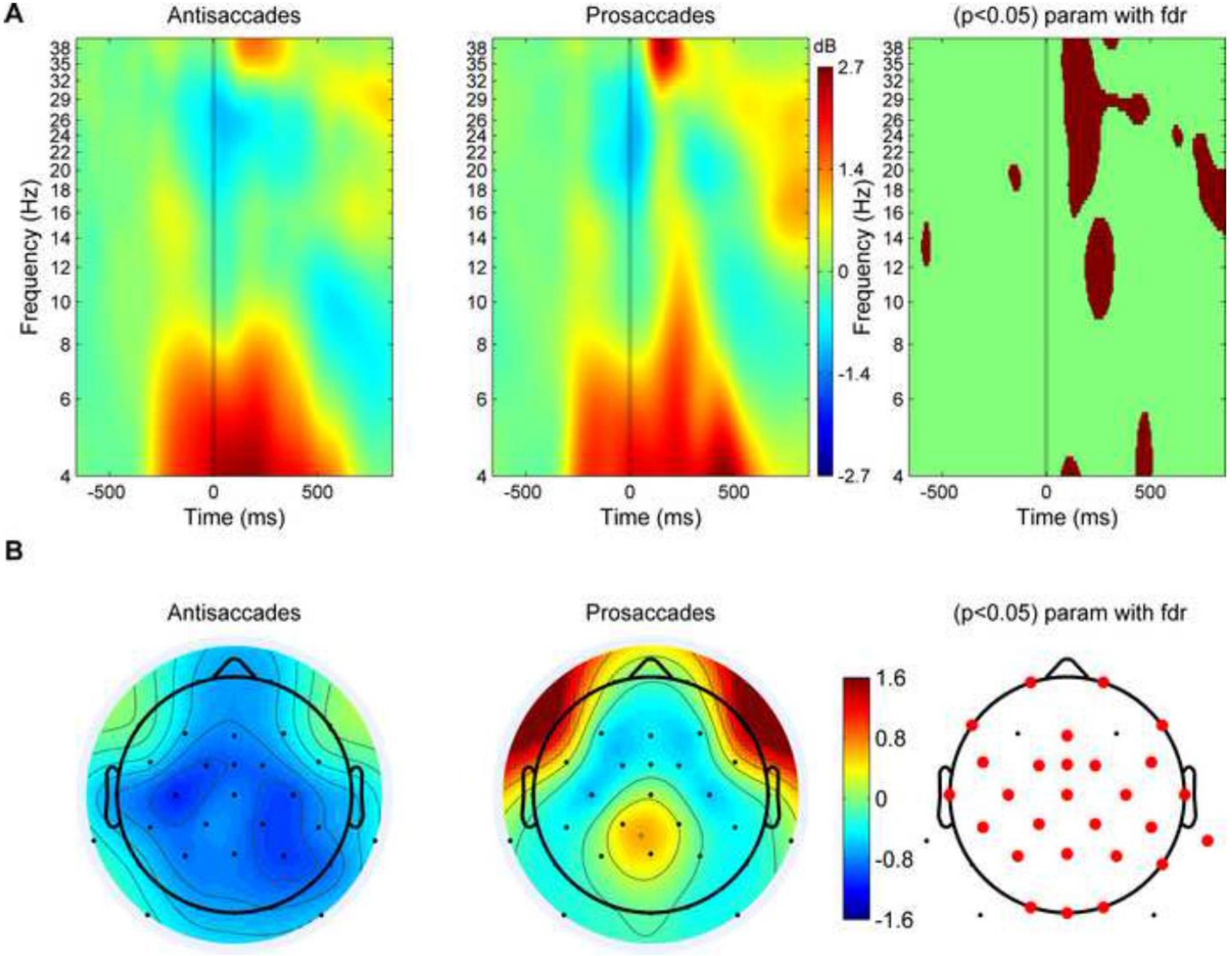

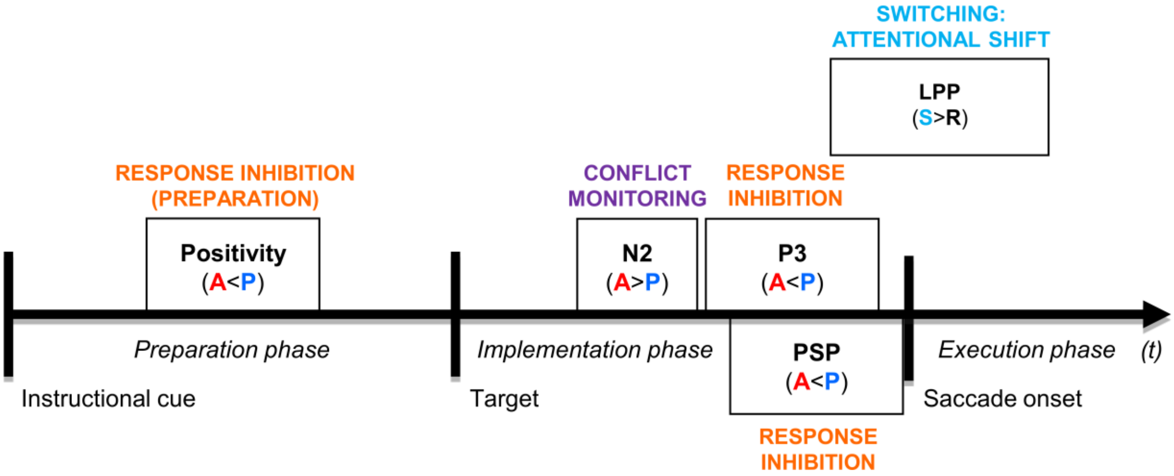

Figure 1. ERP components. Overview of the different ERP components reported in the preparation, implementation and execution phases of saccadic eye movements in (A) cue-locked, (B) target-locked and (C) saccade-locked epochs. PSP: presaccadic positivity; LPP: late parietal positivity; A: antisaccade; P: prosaccade.

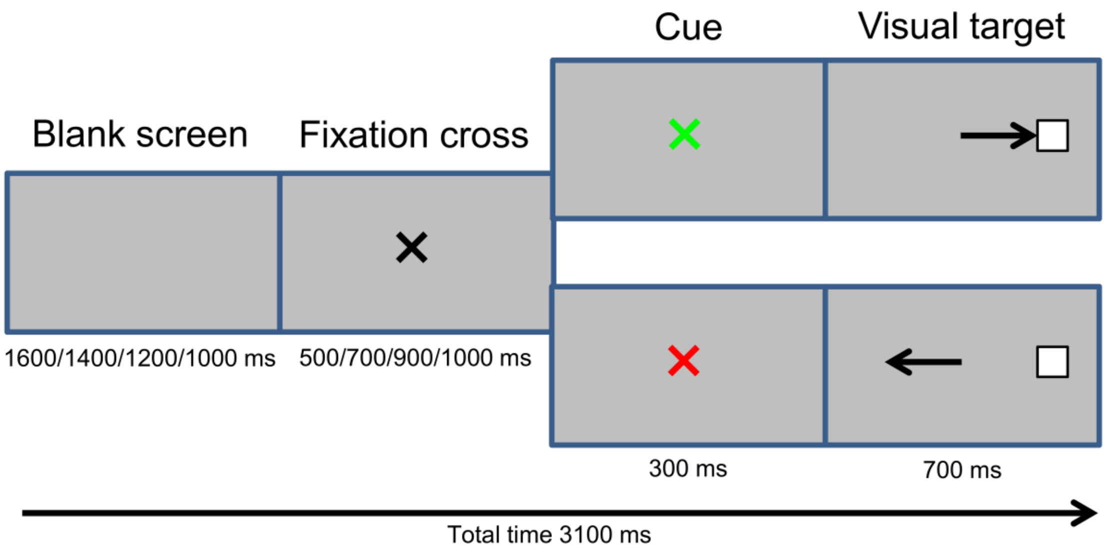

Figure 2. Timing of a prosaccade and an antisaccade trial.

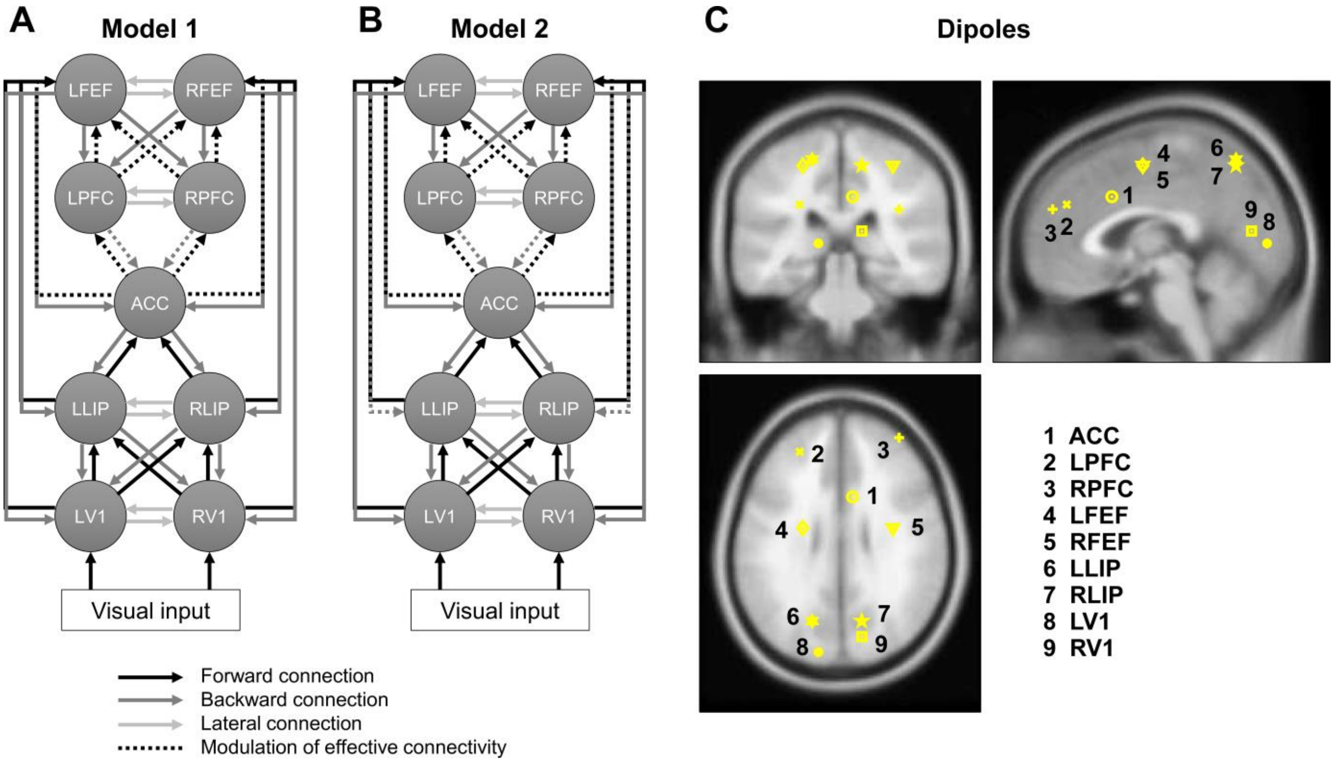

Figure 3. Effective connectivity models tested in a DCM analysis and equivalent current dipole locations. A, B The neuronal sources in the models are connected with forward (black), backward (dark gray) or lateral (light gray) connections. Connections that are modelled to vary between experimental conditions are depicted with dotted lines. Two different models were tested using the same architecture but modelling different backward connectivity from FEF to LIP, being invariant in the two experimental conditions (Model 1, panel **A**) or being allowed to vary between the two experimental conditions (Model 2, panel **B**). Connections between LV and FEF as well as LIP and FEF also connect to the contralateral side but are depicted only for the ipsilateral side for the sake of clarity of the figure. **C** Locations of the equivalent current dipoles included in the two models are depicted in an MRI of a standard brain in MNI space. ACC, anterior cingulate cortex; LFEF/RFEF, left and right frontal eye field; LLIP/RLIP, left and right lateral intraparietal area; LPFC/RPFC, left and right prefrontal cortex; LV1/RV1, left and right primary visual cortex.

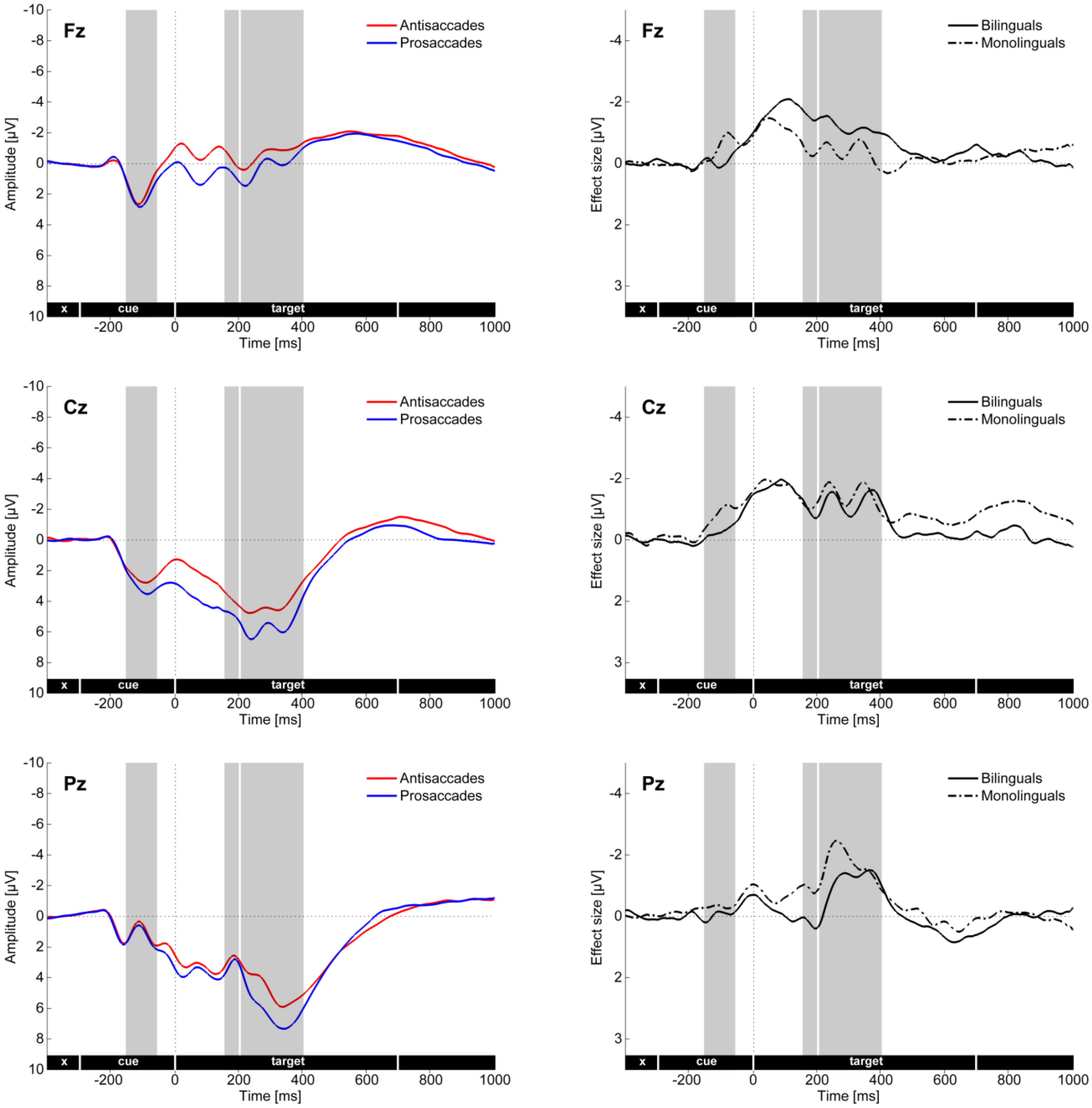

Figure 4. Cue- and target-locked ERPs in the mixed task session on the three midline electrodes. The left panel shows the main effect of Saccade task and the right panel the difference waves (antisaccades minus prosaccades) in the two groups. Gray bars mark the time windows used for investigating the cue-locked positivity effect, as well as the target locked N2 and P3 components.

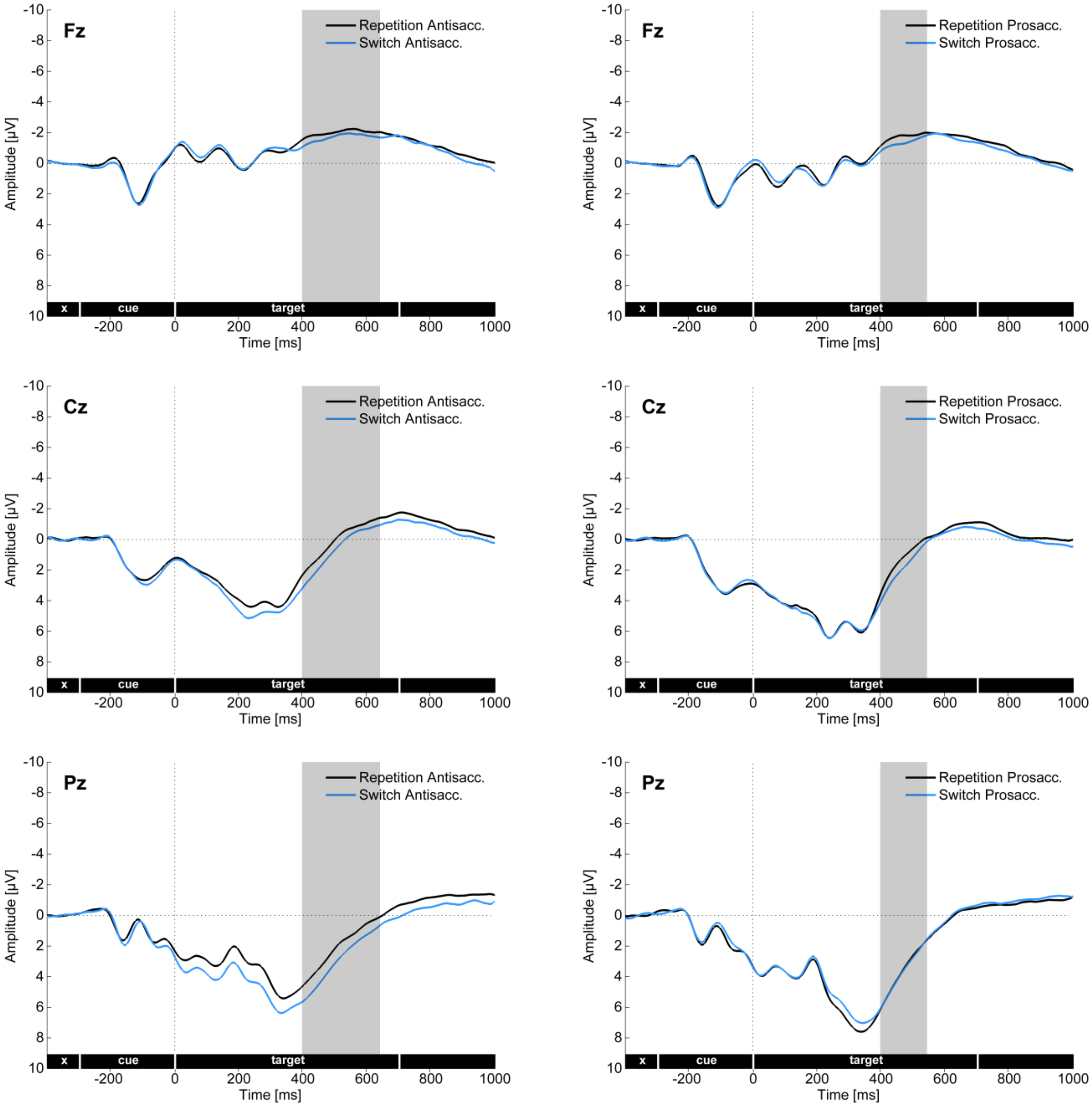

Figure 5. Target-locked ERPs for the Transition types switch and repetition on the three midline electrodes. The left panel shows the ERPs for antisaccade trials and the right panel the ERPs for prosaccade trials, collapsed over the two groups. The gray bar marks the time window used for investigating the LPP component.

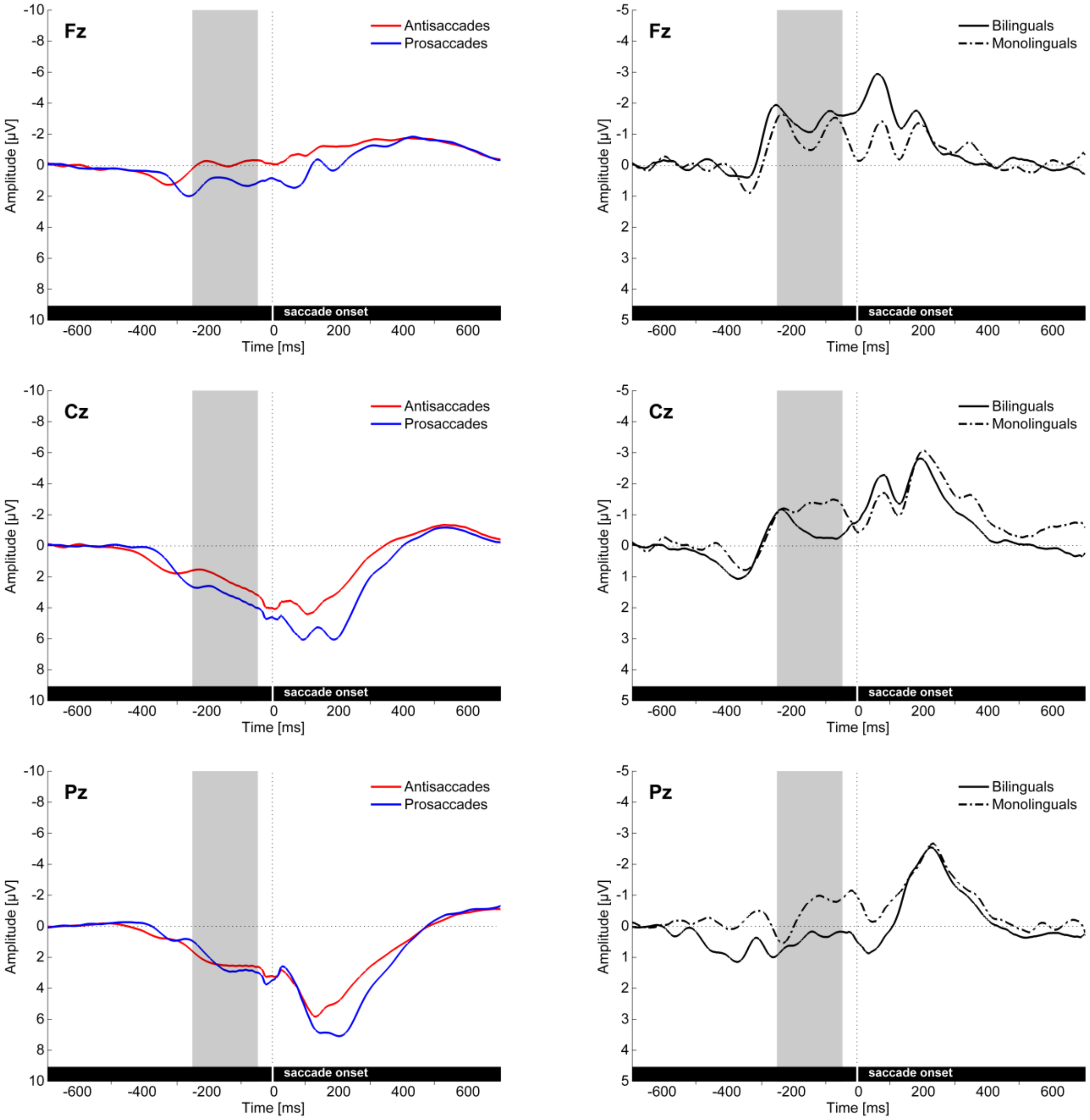

Figure 6. Saccade-locked ERPs in the mixed task session on the three midline electrodes. The left panel shows the main effect of Saccade task and the right panel the difference waves (antisaccades minus prosaccades) in the two groups. The gray bar marks the time window used for investigating the presaccadic positivity (PSP) component.

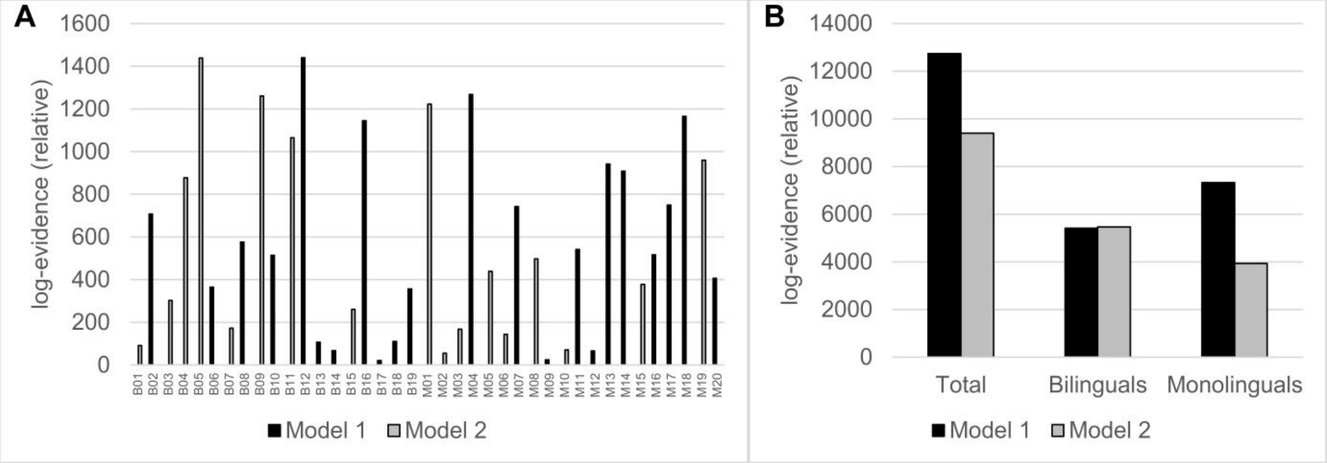

Figure 7. Bayesian model comparison of the two effective connectivity models tested in a DCM analysis. A The relative (compared to the respectively other model) log-evidence for each participant is depicted. For each participant, the model with the relatively higher log-evidence is the ‘winning’ model, i.e. the model which better explains the data. **B** Relative log-evidences added up over subjects are displayed collapsed over both groups as well as for bilinguals and monolinguals separately.

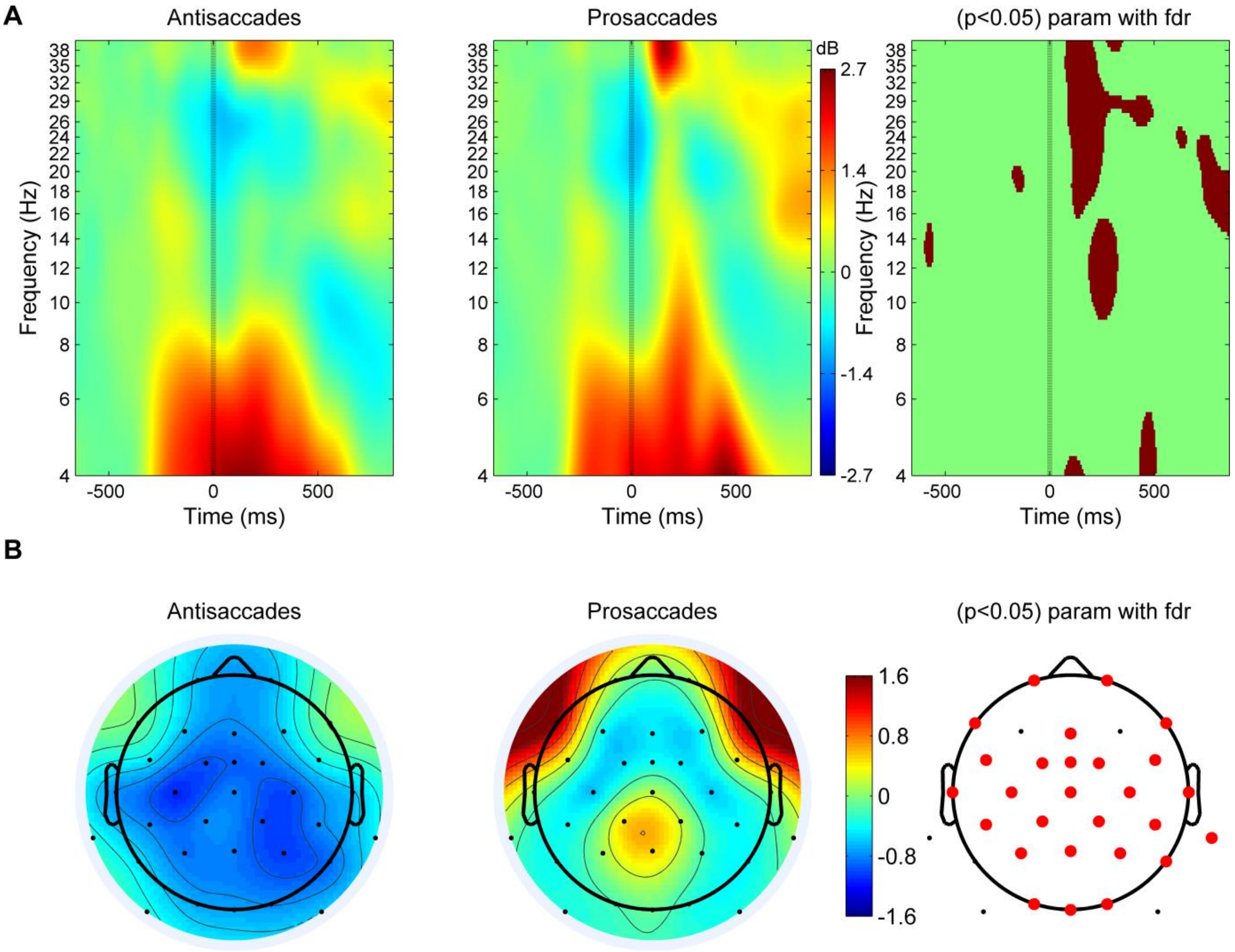

Figure 8. Time-frequency analysis. A Event-related spectral perturbations (ERSPs) time-locked to target onset are plotted for the Cz electrode for antisaccades and prosaccades and a panel for significant ERSP differences between Saccade tasks is displayed on the right side. **B** The beta power decrease at around 150 ms after target onset in antisaccades compared to prosaccades over the central and posterior scalp is plotted at frequency 24 Hz. A panel showing the electrodes with a significant ERSP difference between Saccade tasks in red is plotted on the right side.

PART 3: GENERAL DISCUSSION AND PERSPECTIVES

6. GENERAL DISCUSSION

6.1. MAIN RESULTS AND INTERPRETATIONS OF THE PRESENT THESIS

The present doctoral thesis was centered on the study of the relation between bilingualism and domain-general executive control. The goal was to understand the neurodynamics of domain-general executive control mechanisms in bilingual language processing. In studying the neurodynamics underlying linguistic and non-linguistic control processes in bilinguals and monolinguals, it was aimed to investigate if and which domain-general control processes are involved in bilingual language control, how these processes are reflected at the neuronal level and especially how they are related and influence each other. Moreover, one further focus in the present doctoral thesis also concerned the influence of different parameters in the language biography, e.g. language proficiency, immersion experience in an L2 environment or the frequency of language use, on control processes.

In order to study the impact of bilingualism on conflict monitoring and interference suppression in a task involving a linguistic component, a behavioral study using a Stroop task (Study 1; Heidlmayr, Moutier, Hemforth, Courtin, Tanzmeister, & Isel, 2014) and a neurophysiological (EEG) study using a combined Stroop - negative priming task (Study 2; Heidlmayr, Hemforth, Moutier, & Isel, 2015) were carried out. Study 1 revealed an advantage of bilingualism on inhibitory control, an advantage that was reinforced by the frequency of use of an additional third language and modulated by the duration of immersion in an L2 environment.

Study 2 allowed for the investigation of the neurodynamics of control processes in processing linguistic conflicts. In this study, a reduction of the effect on ERP markers of inhibition (interference suppression; N4 and the late sustained negative-going potential) has been observed for bilinguals compared to monolinguals, an advantage that was reinforced by the frequency of use of the second language. The analysis of the neurodynamics of the underlying neuronal generators showed a crucial role of the anterior cingulate cortex (ACC) in early time windows and the prefrontal cortex (PFC) slightly later in the realization of the combined Stroop – negative priming task, and this implication of neuronal sources was more pronounced in bilinguals compared to monolinguals.

Study 3 aimed at examining to which extent the control processes involved in bilingualism are domain-general control processes that are shared between linguistic and non-linguistic cognitive domains. Thus, the impact of bilingualism on oculomotor control was examined in a neurophysiological (EEG) study using an antisaccade task (Study 3; Heidlmayr, Doré-Mazars, Aparicio, & Isel, submitted). An advantage of bilingualism was found on ERP markers of conflict monitoring (N2) as well as inhibition (response inhibition; cue-locked positivity, target-locked P3, saccade-locked presaccadic positivity (PSP)) and the inhibitory advantage was reinforced by the L2 proficiency and by immersion experience. Critically, a bilingual advantage on the markers of inhibition was found at the three different stages of processing, i.e. the cue-locked *preparation phase*, the target-locked *implementation phase* and the saccade-locked *execution phase*. Furthermore, analyses on effective connectivity, i.e. concerning the influence of the activity in one neuronal region on the activity in another region, revealed a crucial role of the ACC in bilinguals and of the PFC in monolinguals in processing the antisaccade task suggesting that bilinguals benefit from more efficient conflict processing in a non-linguistic task.

In conclusion, the main findings collected in the present doctoral thesis, were (1) the behavioral and neurophysiological evidence of enhanced conflict monitoring and inhibitory capacities in bilingualism, (2) the more efficient dynamic interplay between anterior cingulate cortex and the prefrontal cortex in executive control in bilingualism, and (3) the modulatory impact of the individual language background on executive control efficiency. The present findings lend support to psycholinguistic theories postulating that domain-general executive control processes - that are shared between different cognitive domains - are involved in the control of languages in bilingualism. Moreover, the activation and interplay of the neuronal generators suggest that the experience in handling more than one language leads to more efficient neuronal processing of conflict monitoring and inhibitory control, amongst others in the ACC and the PFC, and also leads to a more efficient interaction between these regions. This research contributes to our understanding of neuroplastic changes during sustained multiple language use and of the neuroplastic adaptations underlying strengthened domain-general executive control. The sustained possibility of suffering interferences between languages is inherent to the bilingual experience and appears to lead to a reinforcement of conflict monitoring and inhibitory control in order to meet communicatory requirements in both languages.

6.2. SIGNIFICANCE OF THE PRESENT RESEARCH

The present research contributes to our knowledge of the tight relation and interplay between the neurocognitive networks of language and control processing. One key statement issued from the present research is that neurocognitive processes cannot be appropriately understood without considering their close interrelation with neurocognitive processes in other cognitive domains. In the present doctoral thesis, the contribution to a further elucidation of a mutual and highly dynamic relation between executive control and bilingual language processing demonstrates that there is a very specific degree of malleability that allows to adjust – in the short run – the strength of control applied in a given neurocognitively demanding situation and – in the long run – an improvement of the capacity of the repeatedly required control processes.

The basic assumption under the theoretical position that domain-general control is involved in and shared by different domains is directly related to the broader theoretical framework of *embodied/grounded cognition*. Embodied cognition theories feed the debate on the main question of the shared vs. distinct nature of linguistic and sensory-motor processing in handling natural language. Increasing neuroimaging and neurophysiological evidence supports the view of a distributed interactive systems account (cf. *embodied cognition* or *grounded cognition*; Barsalou, 2010; Pulvermüller, 2005), e.g. the co-activation of classical language and motor regions during action word processing (Hauk, Johnsrude, & Pulvermüller, 2004) or the influence of word reading on motor control (Gentilucci, Benuzzi, Bertolani, Daprati, & Gangitano, 2000). As for executive control, manifold empirical evidence lends support to the theoretical accounts claiming a shared nature of (domain-general) control between cognitive domains, i.e. showing overlapping neuronal activation for linguistic and non-linguistic control (De Baene, Duyck, Brass, & Carreiras, 2015; de Bruin et al., 2014; Weissberger et al., 2015). The present research contributes to our understanding of shared substrates between linguistic and non-linguistic control and the activity-dependent changes in network (effective) connectivity as a function of linguistic and environmental demands. Moreover, the present findings also show the dynamic adjustment of the interplay between control processes. Further research is required in order to better understand how control processes and their neural bases are related but it shall be stated that the study of control processes in isolation might not reveal the most accurate picture but that they should always be considered within their tight interrelation with other control processes and as well as with cognitive processes in other domains.

Beyond the progress on our fundamental knowledge on the relation between executive control and multiple language use, the present research is of relevance for the fields of research on language acquisition over the life span, language teaching and learning, therapeutic patient care or healthy and pathological aging. Language teaching and learning takes place to a large part in the classroom context and only to a limited degree in immersion situations. Without questioning the benefits of explicit learning of a second language as empirically demonstrated in previous studies (Mårtensson et al., 2012;

among others), the relevance of immersion experience and its relevance for implicit knowledge acquisition should be underlined, while keeping in mind that language learners at different ages require different degrees of explicit and implicit language knowledge transmission (Paradis, 2009), which implies different control demands with different age of acquisition. Moreover, beyond the age of acquisition of a second or further language, the level of proficiency and the immersion experience are core factors that structure the neurocognitive representation of the second language and critically the control demands required for managing the appropriate use of the L1 and L2, for which evidence has been provided in the present thesis. Immersion experience is a neurocognitively highly demanding situation and requires neuroplastic adaptation to modified linguistic and environmental constraints, especially during initial immersion experience. It has been shown experimentally that immersion experience as compared to classroom learning involves different control demands (Linck et al., 2008, 2009), whereas it is not yet clear which precise differences there are. Moreover, control demands most likely change in different stages during prolonged immersion, given the observed impact of the duration of immersion on control capacities (Heidlmayr et al., 2014, submitted; Nicolay & Poncelet, 2013). However, the issue of longitudinal changes of control demands in immersion is largely understudied and it will be of crucial importance to tackle this and related questions with a longitudinal approach in order track different phases of neuroplastic adaptation.

Moreover, the present findings of neuroplasticity over the lifespan help elucidating the time frame and persistence of neurocognitive adaptations as a function of linguistic constraints. Improving the knowledge on lifelong neuroplasticity has an important implication for therapy in pathological cases involving language impairment, e.g. in (stroke-induced) aphasia (Ansaldo, Marcotte, Scherer, & Raboyeau, 2008; Green, 2005; Green et al., 2010; Green & Abutalebi, 2008; Marcotte, Perlbarg, Marrelec, Benali, & Ansaldo, 2013), or patient care-taking in a non-native language environment. Furthermore, the upbuilding of a cognitive reserve against a rapid cognitive decline in aging is an issue on which we have recently learned a lot from research on activity-dependent neuroplasticity (Antoniou, Gunasekera, & Wong, 2013; Clare et al., 2014; Grant et al., 2014), but many questions remain to be elucidated. This research can help improving initiatives that aim at preserving health in aging and to improve the therapy and the patient wellbeing in case of pathological aging.

7. CONCLUSION

In conclusion, the main findings collected in the present doctoral thesis, were (1) the behavioral and neurophysiological evidence of enhanced conflict monitoring and inhibition in bilingualism, (2) the more efficient dynamic interplay between anterior cingulate cortex and the prefrontal cortex in executive control in bilingualism, and (3) the modulatory impact of the individual language background on executive control efficiency. The present findings lend support to psycholinguistic theories postulating that domain-general executive control processes are involved in the control of languages in bilingualism. Moreover, the activation and interplay of the neuronal generators suggest that the experience in handling more than one language leads to more efficient neuronal processing of conflict monitoring and inhibitory control, amongst others in the ACC and the PFC, and also leads to a more efficient interaction between these regions. This research contributes to our understanding of neuroplastic changes during sustained multiple language use and of the neuroplastic adaptations underlying strengthened domain-general executive control. Each bilingual, who has intrinsic perceptive and cognitive characteristics, lives and experiences a unique linguistic experience and the neuronal plasticity over the life span will permit to flexibly adapt to the conversational and interactional constraints imposed by the environment. Moreover, this individual experience is probably influenced by motivational and emotional nonlinguistic factors. Recent research has considerably advanced our understanding of the neuronal and cognitive changes accompanying bilingual experience but there are many questions that yet require to be answered. Future research should foster the integration of research on different levels, from the micro-level, i.e. the level of individual neurons, to the macro-level involving neurophysiological techniques such as EEG or MEG, neuroimaging and cognitive modelling. As it has proven successful in other scientific domains, such an integrative account is most promising to promote our understanding of neuronal and cognitive plasticity in general and the role it is playing in bilingualism in particular.

8. RESEARCH PERSPECTIVES

8.1. CONTROL OF CROSS-LANGUAGE INTERFERENCE

The present research work contributed to our knowledge of domain-general control involvement in bilingual language processing, by means of tasks involving a linguistic or a motor component. It has been stated that different control processes are involved and strengthened in bilingual language use according to the specific requirements of control in different profiles of bilingualism. However, it is now of interest, how the involvement of these control processes actually manifests in bilingual language use, e.g. how different control capacities allow to cope with cross-language interference. Only few previous studies have systematically studied how the differences in control capacity manifest in cases of actual cross-language interference and which role a bilingual control advantage hence may play. For instance, Filippi et al. (2012) showed that bilinguals better manage to resist sentence-level interference than monolinguals. However, much needs to be learned about the role of a bilingual control advantage in interference control on different levels of linguistic processing, i.e. syntactic, lexical, morphosyntactic, phonological or phonetic processing by taking into consideration separately at each of these processing levels, if possible, the respective characteristics of the mother tongue and the second language. Furthermore, this question should also be linked to the specific language use in different dominant interactional contexts. As for the experimental implementation, one may think of manipulating the degrees of difficulty and cross-language interference, by varying morphosyntactic complexity, phonological interference or the combination of typologically close or distant languages, etc. The question of the advantage of increased control capacities in bilingual language use is also of interest in second language learning in different age groups. For instance, it might be of interest to think about a parallel implementation of methods focusing on cognitive control strengthening in order to facilitate second language learning in sequential bilingualism.

8.2. NEURONAL BASIS OF PLASTICITY IN MULTIPLE LANGUAGE USE

The present research work laid a strong focus on elucidating neuroplastic processes in late second language learning. To do so, neurophysiological measures were chosen due to the high temporal resolution, which allows us to study temporal dynamics and relations of control processes. Moreover, source reconstruction analyses and effective connectivity analyses at the source level were used to trace these dynamics at a spatially more fine-grained level. The experimental approach in the present thesis was of a holistic nature, i.e. in analyzing the neuronal activity at the macro-level. However, it was aimed at relating the observations obtained at the macro-level to micro-level dynamics, which are elaborated in the introduction section, especially focused on the core issue that is neurodynamics. Further research should reinforce the integration of knowledge obtained on different scales, in integrating research on cytoarchitecture, cell physiology, different levels of electrophysiology, intra-operative measurements, primate studies, neuroimaging and neurophysiological research (see also, Carter & van Veen, 2007).

8.3. LONGITUDINAL APPROACHES

The link between environmental linguistic constraints and longitudinal changes in the involvement of control in language production is largely understudied but is of crucial importance for our understanding of the dynamics of adaptation in language production processes. As it has been claimed by Hernandez (2009) that previous research has adopted a rather static view on variables in bilingual language processing, e.g. age of acquisition or proficiency, an approach that is not perfectly adapted for studying an inherently non-linear dynamical process, such as bilingual language processing, which also strongly depends on the communicative demands that are imposed on the language processing system. Moreover, as we pointed out with the study of Golestani and Zatorre (2009) investigating individual differences in learning to discriminate non-native sounds, individual differences certainly play an important role in the variability of executive function capacity, as can be seen for instance in section 1.5.5. It is first of all essential to assess language background information on factors such as the following described above (section 1.5): *age of second language acquisition*, *second language proficiency*, *second language immersion experience* and the *interactional context and frequency of language switching*. However, in order to reduce confounding factors, and specifically the impact of individual differences, and to isolate the effect of factors of interest, longitudinal studies could provide valuable information. As an example, different durations of immersion experience in an L2 environment may bring about changes in control demands, and these changes might not follow a linear pattern. Different phases of immersion experience and intense late second language learning may also involve a degree of vulnerability when the L2 needs to be integrated into the language system in which the L1 is well entrenched (A. Hernandez et al., 2005). This degree of fragilisation of the consolidated language system during L2 learning and acquisition may come along with stronger top-down control in order to cope with the increased complexity and fragility in the language system. Consequently, in future research, longitudinal approaches should be adopted in order to better capture the dynamic nature of executive control involvement in language production and the influence of the environmental linguistic constraints while reducing the influence of confounding factors to a minimum.

8.4. INTERACTIONAL AND CONVERSATIONAL CONTEXT

The relevance of the interactional context (Green & Abutalebi, 2013; Green & Wei, 2014) and the frequency and awareness of language switching (Rodriguez-Fornells et al., 2012) for the involvement of executive control in bilingual language processing have been discussed earlier (cf. section 1.5.4). In order to learn more about the control processes involved in different interactional contexts, it may be instructive to take a longitudinal approach involving follow-up testing of individuals at different time points during immersion experience. Different combinations of the dominant interactional context of origin and the new context is supposed to produce different patterns of difficulty and hence of adaptation requirements. Moreover, beside mid- and long-term adaptation during immersion, it is highly interesting how short-term dynamic adaptation processes take place. As an example, one may want to investigate the neurocognitive changes in control involvement during the conversational interaction of two speakers who impose constraints on the respectively other speaker through their language capacities and use. Only few studies have previously addressed the issue of control in online conversational interaction in bilinguals and there is first evidence that the difficulty of production is higher in dialogue than monologue speech as well as in L2 than in L1 production (Pivneva, Palmer, & Titone, 2012). Moreover, L2 proficiency and inhibitory control capacity were found to be linked to more efficient production in bilinguals (Pivneva et al., 2012). Kootstra et al. (2009; 2010) proposed the *interactive alignment model* of bilingual processing in dialogue which aims at bringing together constraints from societal language use and individual language use in code-switching and also proposed methods to investigate different types of language switching. This model assumes, that (bilingual) dialogue aims at delivering messages as well as mutual understanding, which is a cooperative behavior involving the alignment to the speech at different linguistic levels (semantics, lexicon, syntax, phonology, etc.) of the respective dialogue partner. In a dialogue between bilinguals mastering the same languages, the dialogual exchange can involve specific patterns and frequencies of code-switching. Moreover, bilingual individuals also rely on contextual information in order to adapt their language use to the interlocutor (Molnar, Ibáñez-Molina, & Carreiras, 2015). Based on the assumption that in bilingual conversational interaction the speaker alignment involves the mutual alignment to a single language in use or to a pattern and frequency of code-switching - which also implies a strong co-activation of both languages - one may ask which control demands are specifically involved and how they change over time. Neuroimaging and neurophysiological investigation of conversational interaction of two or more speakers may reveal a lot about the adaptive changes taking place when speakers are required to adjust to the language constraints imposed by one another. We plan to approach the question of the relation of the interactional context and the efficiency of managing grammatical transfers during auditory processing of sentences in a second language by testing bilinguals in different linguistic contexts (Heidlmayr, Kail, Isel).

8.5. MOTIVATION AND EMOTIONAL ASPECTS IN BILINGUALISM

One question that has only be tackled to a limited extent in the present research work concerns the role of motivation and emotion in language control. There is an evident interaction between motivation and cognition, and specifically the high impact of motivation on the outcomes of learning, but the relation between motivation and cognition remains largely understudied (Braver et al., 2014). The investigation of the role of motivation in second language learning and acquisition – as well as other emotional aspects tied to language, such as the valorization or affect associated with a given first or second language – can help explaining a large part of language learning outcomes (Csizér & Dörnyei, 2005; Dörnyei, 2003; Gardner, 2007; Somerville & Casey, 2010). Note, however, that the experimental operationalization of the factor motivation in studies on cognition in general, and in studies of second language learning in particular is not easy to realize, which can probably explain why it has been set aside in cognitive neuroscience of language until now. Moreover, the motivational and affective value of a language also requires to be understood in its tight association with a cultural context (Dörnyei, 2003; Paradis, 2009). It would be of greatest interest to address the question of how the motivation to achieve high proficiency in a second language relates to the time course and extent of neuroplastic changes. Linked to this motivational factor are strategic behaviors of engaging oneself in this activity, e.g. multiple language use, or immersion experience.

8.6. LESS CAN BE MORE? ON THE OPTIMAL LEVEL OF COGNITIVE CONTROL

Studies interested in the impact of bilingualism on creativity are a valuable contribution to the study of the mechanisms of multiple language control. Hommel, Colzato, Fischer and Christoffels (2011) investigated the impact of bilinguals' second language proficiency on two aspects of creativity, i.e. convergent thinking and divergent thinking. Their findings show that a bilingual advantage in creative processes is modulated by second language proficiency: while highly proficient bilinguals were found to have an advantage in convergent thinking – a process involving strong top-down control -, low proficient bilinguals showed better performance in divergent thinking – a process requiring only weak top-down control implication. These observations corroborate the idea that domain-general control is involved in the control of multiple language use. However, a more nuanced picture has to be drawn than it has previously been done, namely in at least two respects: (1) the idea that different profiles of bilinguals may lead to different patterns in the degree and type of a bilingual advantage in executive control needs to be studied in further detail in order to improve our understanding of control in bilingualism and (2) better top-down control can be advantageous in certain tasks but disadvantageous in others (Chrysikou et al., 2013). Various forms of language mixing and switching can lead to highly creative language productions. The form and strength of cognitive control over the two languages is a determining factor, leading to different forms of lexical and morphosyntactic combination vs. separation (Green & Wei, 2014; Kharkhurin, 2010; Kharkhurin & Wei, 2014). The investigation of the link between executive control, bilingual language use and creativity may provide precious information about the fine-grained adjustment of the strength of executive control in different forms of language use.

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