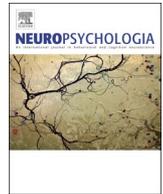




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Language control mechanisms differ for native languages: Neuromagnetic evidence from trilingual language switching

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ARTICLE INFO

Keywords:

Trilingualism
Language control
N400m
Language switching
Auditory speech perception

ABSTRACT

How does the brain process and control languages that are learned at a different age, when proficiency in all these languages is high? Early acquired strong languages are likely to have higher baseline activation levels than later learned less-dominant languages. However, it is still largely unknown how the activation levels of these different languages are controlled, and how interference from an irrelevant language is prevented. In this magnetoencephalography (MEG) study on language switching during auditory perception, early Finnish-Swedish bilinguals ($N = 18$) who mastered English with high proficiency after childhood were presented with spoken words in each of the three languages, while performing a simple semantic categorisation task. Switches from the later learned English to either of the native languages resulted in increased neural activation in the superior temporal gyrus (STG) 400–600 ms after word onset (N400m response), whereas such increase was not detected for switches from native languages to English or between the native languages. In an earlier time window of 350–450 ms, English non-switch trials showed higher activation levels in the inferior frontal gyrus (IFG), pointing to ongoing inhibition of the native languages during the use of English. Taken together, these asymmetric switch costs suggest that native languages are suppressed during the use of a non-native language, despite the receptive nature of the language task. This effect seems to be driven mostly by age of acquisition or language exposure, rather than proficiency. Our results indicate that mechanisms of control between two native languages differ from those of a later learned language, as upbringing in an early bilingual environment has likely promoted automatization of language control specifically for the native languages.

1. Introduction

In daily life, bilingual speakers carry out a complex task of which they may not even be aware: they select and manage their languages without apparent trouble. Bilingual speakers adapt to their conversational partners depending on the conversational setting, which could be a single- or dual-language context, or even a language environment characterised by frequent switching between languages (Green and Abutalebi, 2013). Experimental evidence from many domains of language processing has indicated that lexical access is language non-selective (for a review, see Kroll et al., 2006). The integrative nature of the bilingual lexicon underscores the need for cognitive control over its various languages, to prevent unwanted interference from languages that are not in use.

Language inhibition has often been proposed as a means to prevent such interference. During the use of a non-dominant language, characterised by lower activation levels, lexical representations of the stronger language are assumedly inhibited. In contrast, such suppression is not assumed for a non-dominant language, as its lower activation levels result in less interference during the use of a more dominant language (Inhibitory Control model, Green, 1998). An important factor that affects language control mechanisms is language proficiency, suggesting that control networks are particularly recruited when a weaker second language (L2) is processed (e.g. Abutalebi and Green, 2007).

Evidence for inhibitory control processes has been presented by several behavioural language switching studies, in which asymmetric switch costs during language production were reported. In these

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studies, switches to a dominant language elicited longer reaction times than switches to a less dominant language (Jackson et al., 2001; Meuter and Allport, 1999; Philipp et al., 2007; Tarlowski et al., 2013). After the use of a weaker language, it is assumedly more costly to reactivate the previously suppressed language than to produce a language that has not undergone such suppression. Asymmetric costs have therefore commonly been taken as evidence for an inhibitory control system working to facilitate the use of the relevant language in a given situation (for alternative theoretical accounts see, e.g. Finkbeiner et al., 2006; Philipp et al., 2007; Runqvist et al., 2012; Verhoef et al., 2009).

A study using functional magnetic resonance imaging (fMRI) during a production task in trilinguals revealed activation of the right inferior frontal gyrus (rIFG) and the pre-supplementary motor area (pre-SMA), neural regions related to domain-general inhibition, after switches to L2 and L3 (De Bruin et al., 2014). This suggests active inhibition of L1 during the use of weaker languages. Such inhibitory processes were not seen when switching to L1, thus supporting claims made by the Inhibitory Control model. Other studies on language production found differential activity in areas related to cognitive control for less proficient languages compared to L1 as well, indicating that the language control network is distinctively engaged according to the relative strength of the language (for a review, see Abutalebi, 2008).

Studies on language control mechanisms during language production increase our knowledge on bilingual language processing and control. However, considerably less is known about control mechanisms at play during language comprehension. In language production, lexical items of the target language are actively selected, whereas the receptive bottom-up driven nature of language comprehension arguably does not recruit similar cognitive processes. The few behavioural studies on language switching in receptive tasks often produced symmetric switching costs in reaction times, or no switching costs at all (Macizo et al., 2012; Thomas and Allport, 2000; Von Studnitz and Green, 2002), supporting the notion that active inhibition may not be necessary. Yet, several studies, especially those utilising brain measures, also suggest otherwise. For example, an event-related potential (ERP) study found that an L1 context prior to the experiment, resulted in L1-related N400 priming during the first half of the experiment, and slowed adjustment to an L2 lexical decision task (Elston-Güttler and Gunter, 2008). This suggests that bilingual speakers need time to tune into the current language context. The language network and its lexical representations may undergo inhibition or facilitation according to the language in use.

Various psycholinguistic models reflect the debate on whether bilingual receptive access is fully non-selective or (partly) selective depending on language-specific cues in the language context. In the domain of visual word recognition, the Bilingual Interactive Activation Plus Model (BIA+; Dijkstra and van Heuven, 2002) specifies the bilingual lexicon as fully integrated for the different languages. In this view, top-down processes do not affect the activation state of the words of different languages. This is in contrast to its predecessor, the BIA, which implies that inhibition takes place via the language node belonging to the language not in use (Dijkstra et al., 1998). In bilingual speech perception, in turn, the Bilingual Interactive Activation Model of Lexical Access (BIMOLA; Grosjean, 1988; Léwy and Grosjean, 2008) assumes that the two language networks of a bilingual speaker are independent, yet share many connections. When a bilingual speaker is required to use only one language in a given situation (monolingual mode), one network is strongly activated while the other is subject to inhibitory influences, consequently receiving only weak activation. Feature-, phoneme- and word-based input present in the interactional context can thus enable more language-selective processes. In this respect, the BIMOLA is similar to the IC model (Green, 1998) although both models were developed to explain processing in different language domains, i.e., production compared to perception.

One of the few studies that specifically addressed the auditory modality in language control processes, is an MEG study by Pellikka

et al. (2015), reporting an asymmetric switching cost to spoken native and non-native words in bilateral temporal activation (N400m responses). These results suggest that effects of L1 inhibition can be observed during language reception using time-sensitive neuroimaging. Previous visual ERP studies have showed N400 modulations in response to language switches as well (e.g. Van der Meij et al., 2011; Ruigendijk et al., 2015). The N400 response has been related to semantic processing and word recognition, and is independent of presentation in the visual or auditory domain (for a review, see Lau et al., 2008).

Further evidence for cognitive control during auditory language comprehension comes from an fMRI study on language switching in auditory perception, which reported increased signals in the caudate nucleus and anterior cingulate after switching into the weaker language, areas related to cognitive and executive control (Abutalebi et al., 2007). Furthermore, an fMRI study that investigated switching between L1 and L2 during a phonological judgment task, reported greater activation for the right prefrontal cortex (PFC), the left superior temporal/supramarginal gyrus (STG/SMG), anterior cingulate cortex (ACC), left IFG, and left caudate nucleus after switches to L2, whereas such increased activity was not found for switches to L1 (Hosoda et al., 2012).

Age of acquisition (AoA) is known to have a pervasive effect on language processing, especially concerning phonology (e.g. Piske et al., 2002) and grammar (for a review, see DeKeyser, 2005). A possible reason for the effect of AoA on language processing is the originally proposed ‘critical period’ for language acquisition (Lenneberg, 1967), later regarded as a ‘sensitive period’, after which language acquisition becomes more effortful. Late bilinguals, defined by a later AoA, have shown extended activation of neural regions related to phonological and syntactic processing in their L2, recruiting additional neural resources to process the language (e.g. Consonni et al., 2013; Hernandez and Meschyan, 2006; Perani et al., 2003; Wartenburger et al., 2003), possibly pointing towards more effortful L2 processing. The recruitment of distinct memory networks in early vs. late language acquisition has additionally been proposed as a means to explain the impact of AoA on language processing (Ullman, 2001). Yet, convergence of neural networks underlying the processing of early vs. late languages has been reported as well (for a review, see Abutalebi, 2008).

However, few studies have specifically addressed the effect of AoA on language control processes even if AoA could arguably have an impact on language control via lifelong language exposure. For example, long-term cognitive plasticity caused by AoA or language exposure may cause less dependence on controlled processing, evidenced by a decrease in left prefrontal activity (Perani et al., 2003). A study by Abutalebi et al. (2007) found engagement of prefrontal structures related to language control specifically for a language that had received less exposure across the lifespan. Furthermore, Pellikka et al. (2015) found evidence for inhibition of L1 during language comprehension, although L2 proficiency was comparably high. The participants in this study were highly proficient in their L2 but had a clear difference in the AoA of their languages, with L2 acquired after the age of 9. This points to AoA as an important driver of control mechanisms. In contrast, previous behavioural studies typically found symmetric switch costs in case of high language proficiency, even when AoA differed (Costa and Santesteban, 2004). The exact effect of proficiency and AoA on language control is still unclear.

It has been suggested that early bilingualism enhances cognitive control functions (e.g., Luk et al., 2011), possibly leading to an advantage in executive functions. Experience with language environments where language control is frequently needed, especially early in life, may train these functions. The situations and tasks that recruit language control are, however, not well known. Better understanding of language control mechanisms is likely to shed light on the bilingual training hypothesis as well. The current study focuses on the role of AoA in neural correlates of switching during auditory language comprehension, and addresses the yet unanswered question of how language control is manifested between early acquired, balanced native

languages.

In the current study, we measured MEG responses during an auditory receptive task in which trilinguals were exposed to spoken words in various language switching directions. A direct benefit of using MEG instead of EEG or fMRI, is that MEG, like EEG, has an excellent temporal resolution which makes it possible to see ongoing cognitive processes within a time span of milliseconds, and at the same time, it provides more accurate spatial localization of neural activity than EEG due to magnetic fields being less distorted by the skull (e.g. Cohen and Cuffin, 1983). The trilinguals in this study simultaneously acquired two languages during early childhood and expressed high proficiency in their third later-learned language as well. If cognitive control is exerted through inhibition of stronger languages as predicted by the IC model and BIMOLA, we would expect to see enhanced inhibition after switches between the native languages, as well as after switches from either native language to L2. These effects would assumedly be reflected by enhanced N400m responses, due to increased effort of accessing lexical items after previous inhibition, as seen in Pellikka et al. (2015). However, if top-down language control is not recruited during auditory comprehension, such effects are likely not seen. Taken together, the aim of the current study was to discover whether language control mechanisms differ for native languages compared to languages learned at a later age, a topic that has been understudied thus far.

2. Methods

2.1. Participants

Eighteen trilinguals who grew up as early balanced Finnish-Swedish bilinguals, participated in the experiment (10 female, 8 male, mean age = 23.9 years, SD = 2.9). Finnish and Swedish were acquired during early childhood (Finnish AoA mean = 0.9 years, SD = 1.5, Swedish AoA mean = 0.2 years, SD = 0.7) with a more or less equal exposure to both native languages throughout childhood and young adulthood. Their third language English was mainly learned as a foreign language at school (AoA mean = 9.1 years, SD = 1.9) and grades obtained in the Finnish national matriculation examination ranged from ‘outstanding’ (top 5% of matriculation exam scores, 11 of our participants) to ‘excellent’ (top 15% of matriculation exam scores, 6 of our participants) and ‘very good’ (top 40% of matriculation exam scores, 1 of our participants). Current English language proficiency was self-reported as very high (mean = 5.9, SD = 0.7 on a scale from 1 (elementary proficiency) to 7 (native or bilingual proficiency)). About 50% of the participants reported currently using English in their everyday lives, e.g., at the university or at work. High proficiency levels of the participants were confirmed by a vocabulary test (developed by the University of Ghent; <http://vocabulary.ugent.be/>), with average scores of 65.9% (on average, proficient *native* speakers score 67%, while 33% is considered a high proficient level for L2 learners according to information provided by the University of Ghent). The participants used Finnish on average 40% of the time in their daily life, whereas Swedish and English were used 42% and 18% of the time, respectively. Table 1 contains further details on the language background of each participant.

All participants had normal hearing, reported no somatic or psychiatric conditions (e.g., major depression) that may affect cognitive functions, had no diagnosed neurological impairments or language disorders and did not take medication that affects the central nervous system. Prior to the experiment, all participants signed an informed consent. The study was approved by the Helsinki and Uusimaa Hospital District Ethics Committee.

2.2. Stimuli

The stimuli consisted of Finnish, Swedish and English spoken nouns. In each language, 486 trials were used, consisting of 260 non-switch trials, 140 language switch trials and 86 target word trials (animate

concepts for which the participants were to give a response). Altogether, the participants ran through 1458 trials (3 × 486). The stimuli were monomorphemic and did not include compound words. Cognates and words that were phonetically too similar were excluded: only words that differed in at least two phonemes were included. None of the stimuli consisted of words that shared the first three phonemes, to limit partial activation of phonetically similar words later in the sequence.

The experimental words were between 3 and 9 phonemes long, with an average phoneme length of 5.14 (SD = 1.14) for Finnish words, 5.14 (SD = 1.43) for Swedish words and 5.15 (SD = 1.73) for English words. Word frequency was matched across the three languages, with average per million log frequencies of 1.51 (Finnish), 1.51 (Swedish) and 1.56 (English). Frequencies of Finnish and Swedish words were obtained via computerized search program WordMill, a newspaper-based corpus that contains 22.7 million Finnish and 24.2 million Swedish tokens (Laine and Virtanen, 1999). Frequencies of English words were obtained from the Celex corpus (<http://celex.mpi.nl>), based on the COBUILD written log frequency of each word.

All words were spoken by a trilingual female speaker, who grew up using all three languages with no noticeable accent in any of the three languages based on evaluations by a native speaker of each language. The stimuli were recorded as 24-bit, 44.1 kHz single channel audio files. Sound files were modified using Adobe Audition software (version 3.0), including normalisation to an equal loudness contour, and linear fading of the last 10 ms of each audio file. To ensure equal duration between the three languages, the tempo of the Finnish words was increased by 9%, while the tempo Swedish words was increased by 5%. These modifications did not result in any pitch changes and were still deemed natural by a native speaker of these two languages. After manipulation, the average duration was 693 ms (SD 136 ms) for the Finnish words, 692 ms (SD 119 ms) for Swedish words and 693 ms (SD 122 ms) for English words.

2.3. Procedure

A script written in Presentation 14.4 defined the stimulus presentation. Auditory stimuli were presented in a pseudorandomized order, starting with 3, 4 or 5 words in one language followed by a switch to another language. In this manner, neural responses to all six possible switching directions were obtained (Finnish to Swedish/English, Swedish to Finnish/English and English to Finnish/Swedish). Fig. 1 shows an illustrative example of the paradigm.

Each language thus consisted of a set of 486 words which were only presented once, no repetitions of the same word were used to avoid familiarity effects that could modulate the response of interest. We furthermore attempted to avoid the use of the same concepts as much as possible (for example, we avoided using the word ‘dog’ in all three languages). If instances of the same concept occurred, they were not placed in close proximity of each other, by inserting at least 12 intervening trials. Moreover, semantically highly related concepts did not occur in close proximity of one another, eliminating possible unwanted priming effects. A final overview of stimuli characteristics per condition (three non-switch conditions, six switching directions and three sets of target words) can be found in Table 2.

Two experimental lists were constructed in order to minimise item-related noise, which differed in word presentation order. Each list consisted of four blocks that were ordered according to a latin-square design, where each of the blocks represented a different presentation order of the languages. The order was randomised so that the direction of the switch would not be predictable. Half of the participants were assigned to the first list, and the other half to the second experimental list.

Participants were instructed to move as little as possible, and avoid blinking, or alternatively, close their eyes. To ensure constant attention was paid to the stimuli, their task was to listen closely to the words they heard, and raise their right thumb each time they heard a target word; a

Table 1

Linguistic background of all participants, including the age of acquisition of their three languages, self-reported proficiency on a scale of 1–7, and the percentage of language use for each of the three languages.

	Age	Age of acquisition			Proficiency (scale 1–7)			Current use of language in %		
		Finnish	Swedish	English	Finnish	Swedish	English	Finnish	Swedish	English
S1	31	0	0	9	7	7	7	25	15	60
S2	25	1	0	9	6	7	5	70	20	10
S3	25	3	0	9	6	7	6	30	50	30
S4	25	0	3	10	7	7	6	30	50	20
S5	25	0	0	9	7	7	5	40	45	15
S6	24	3	0	6	7	6	7	25	25	50
S7	26	0	0	9	7	7	6	45	50	5
S8	23	3	0	11	7	7	6	60	30	10
S9	24	5	0	6	6	7	6	30	45	20
S10	20	3	0	11	7	7	6	20	65	15
S11	25	0	0	9	7	7	6	20	75	4
S12	23	0	0	7	7	6	5	60	30	8
S13	25	0	0	10	7	7	6	40	40	20
S14	21	0	0	10	7	7	6	40	45	15
S15	26	0	0	13	7	7	5	40	40	20
S16	18	0	0	5	7	7	7	15	65	15
S17	20	0	0	10	7	7	5	50	45	5
S18	24	0	0	9	7	7	6	80	15	5
Average	23.9	1.0	0.2	9.0	6.8	6.9	5.9	40	42	18

noun that referred to an animal or person (animate words). These target words made up 18% of the total trials in each language, but never occurred at language switch position, only as non-switches, to avoid motor-induced interference on trials of interest. A response device generated a trigger signal for each thumb lift via optical fibers. The experiment was preceded by a short practice round (11 trials per language), to familiarize the participants with the speed of word presentation and the experimental task. These trials were not repeated during the actual experiment.

To avoid motor-induced interference related to the thumb lift, the stimulus-onset asynchrony (SOA) was kept to 1600 ms, so that possible motor effects had subsided by the time the next word was presented. Each of the four experimental blocks took about 10 min, resulting in a total measurement time of around 40 min. Short breaks were given between blocks. After the MEG measurement, the participants were asked to complete the English vocabulary test, which took around 5–10 min. Including preparation and aftercare, the total duration of the experiment was about 80–90 min.

2.4. MEG data acquisition

The MEG measurements were done with a 306-sensor Elekta Neuromag neuromagnetometer (Elekta Ltd., Helsinki, Finland), with a

Table 2

Descriptive statistics on stimuli characteristics per condition, including log frequency, number of phonemes and word duration. Mean values and standard deviations (SD) are reported.

	Log frequency	Phoneme number	Word duration
Fin non-switch	1.5 (0.5)	4.9 (1.0)	654 (122)
Swe non-switch	1.5 (0.5)	4.8 (1.2)	682 (126)
Eng non-switch	1.5 (0.5)	5.0 (1.8)	678 (116)
Fin-Swe switch	1.5 (0.6)	4.9 (1.2)	680 (120)
Fin-Eng switch	1.6 (0.5)	5.0 (1.8)	692 (121)
Swe-Fin switch	1.6 (0.6)	5.1 (1.1)	693 (143)
Swe-Eng switch	1.6 (0.4)	5.2 (1.6)	684 (123)
Eng-Fin switch	1.6 (0.6)	5.0 (1.0)	653 (114)
Eng-Swe Switch	1.5 (0.5)	4.9 (1.2)	677 (124)
Finnish targets	1.4 (0.6)	5.9 (1.2)	699 (118)
Swedish targets	1.4 (0.5)	6.0 (1.7)	692 (121)
English targets	1.4 (0.5)	5.9 (1.5)	683 (117)

600-Hz sampling rate and a 0.03–200 Hz bandpass filter in a magnetically shielded room (Euroshield, Eura, Finland) at the BioMag Laboratory. Vertical and horizontal electro-oculograms (EOG) were recorded simultaneously. Prior to data acquisition, the exact location of the head relative to the MEG sensors was determined by four head-

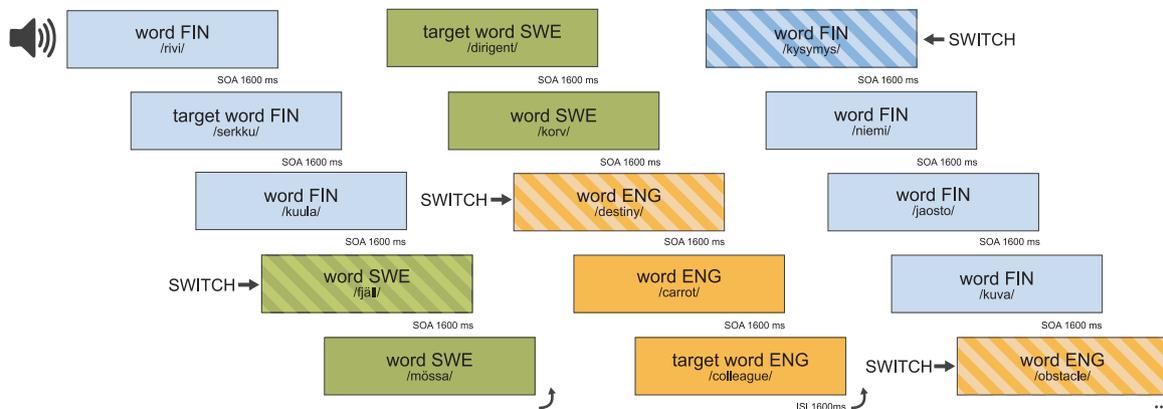


Fig. 1. Example of the paradigm. Three, four or five words in one language were followed by a sequence of words in another language. Target words made up 18% of the total words in each language, and prompted the participant to respond with a thumb lift. Responses to six different switching directions were obtained with this rapid switching paradigm.

position indicator (HPI) coils on the forehead and mastoids. The location of the coils relative to the nasion, and left and right preauricular points were obtained by means of a 3D digitiser (Fastrak, Polhemus, Colchester, VT, USA).

2.5. MEG data analysis

Continuous MEG raw data were preprocessed and cleaned with the spatio-temporal signal space separation method (tSSS: MaxFilter™ software) using a 6-s time window and subspace correlation limit of 0.98 (Taulu and Simola, 2006). With tSSS, magnetic interference coming from outside of the sensor array is suppressed and other measurement artifacts from nearby sources (e.g., the heart) are reduced. Because the participants were given a short break halfway through the experiment, MaxFilter™ software was used to transform data from the blocks after the break to match the head position coordinates of the first block. MEG responses were averaged: a 1200 ms time window was utilised which included a 200 ms prestimulus baseline. The data were filtered offline with a 0.01–45 Hz frequency band.

Further data analyses were done with BESA Research 6.0 Software (BESA GmbH, Munich, Germany). Artefacts related to ocular movements were removed with a principal component analysis (PCA; Ille et al., 2002), using 5000 fT/cm limit for gradiometers. The final data set included 67 trials (SD = 4.3) on average for all six switching directions, and 250 (SD = 18.9) trials for the non-switches in each of the three languages. For the source reconstruction, a BESA built-in 4-shell standard spherical head model was used. PCA revealed two major sources in the epoch length of – 200 to 1000 ms, based on averages of Finnish, Swedish and English non-switch trials. The largest source, peaking around 500 ms, explained on average 79.8% of variance in the full epoch, whereas the second source, peaking around 250 ms, explained another 15.3%. The largest neural source was first modelled for each condition, as Equivalent Current Dipoles (ECDs) (Hämäläinen et al., 1993; Salmelin, 2010). In dipole modelling, all 204 gradiometers were utilised. This was done to reduce subjectivity related to sensor selection (Pylkkänen et al., 2006). Bilateral dipoles for the major source were fitted in the 350–550 ms time window in which the N400m responses were stable and clear in the sensor signals, and were localized in the Superior Temporal Gyrus (STG), average Talairach coordinates 44, – 9, 11 and – 44, – 13, 13. The resulting Goodness of Fit (GoF) was on average 85%.

A Laplacian weighted minimum-norm algorithm for distributed source analysis (LORETA) performed in the 200–300 ms and 350–550 ms time windows confirmed the bilateral STG activation, and localized the smaller second neural source in the left and right Inferior Frontal Gyrus (IFG) in the earlier time window (See [Supplementary Fig. 1](#)). ECDs were thereafter fitted at individual coordinates for each subject, resulting in an average Goodness of 83% for this multidipole model (the previously located bilateral STG and the added bilateral IFG) in the 200–300 ms time window where neural strength was peaking. The average Talairach coordinates of IFG sources were 33, 27, 4 and – 33, 27, 4.

2.6. Statistical analysis

In all subjects, bilateral dipole sources in the STG and the IFG were used to explain the measured data for each condition (non-switched words and each switching direction). The average strength of the left and right hemisphere N400m and the earlier frontal response sources was measured from the resulting source waveforms for each individual and condition in the 400–600 ms, and the 350–450 ms time windows, where differences between conditions were most pronounced. There were no differences in the 200–300 ms time window, hence, this time window will not be discussed further.

Using repeated-measures ANOVA, we first analysed the differences between all non-switched and switched stimuli using Switch (2 levels:

no switch, switch) and Hemisphere (HS, 2 levels: left, right) as within-subject factors for each source separately. To compare responses to words of the three different languages during non-switches only, we used a repeated-measure ANOVA on Language (3 levels: Finnish, Swedish and English) and Hemisphere (HS, 2 levels: left, right).

Thereafter, differences between language switching directions were analysed using a repeated-measures ANOVA to compare the effects of Base language (i.e., the language that the participants switched *from*; 3 levels: Finnish, Swedish English), Target language (i.e., the language that the participants switched *to*; 3 levels: Finnish, Swedish, English), and Hemisphere (two levels: left, right).

A linear mixed effects analysis was performed on the behavioural data (RTs and error rates) to compare responses to target words (animate words) in Finnish, Swedish and English, with fixed effects including Language and random effects including intercepts for subjects and by-subject random slopes for the effect of Language. Additionally, a one-way ANOVA was performed to investigate differences in error rate between the languages.

Statistical analyses were performed with SPSS Statistics 24 software (IBM Corp., Armonk, NY, United States). To all analyses of variance, Greenhouse-Geisser corrections were applied wherever appropriate and only corrected p-values are reported in the results. To Post Hoc analyses, Bonferroni corrections were applied.

3. Results

3.1. STG source waveforms

The ANOVA (Switch × HS) on switches compared to non-switches showed a main effect of Switch ($F(1,17) = 13.29$, $MSE = 9.63$, $p = 0.002$, $\eta^2 = 0.439$) but only a trend for Hemisphere ($F(1,17) = 3.70$, $MSE = 413.59$, $p = 0.071$, $\eta^2 = 0.179$) for the N400m responses. Switches elicited stronger N400m activation at 400–600 ms than non-switches (mean 27.5 vs. 24.8 nAm, resp.). [Fig. 2](#) illustrates the mean strength of the N400m activation in the left and right hemispheres to Finnish, Swedish and English non-switches. The ANOVA (Language × HS) performed on non-switched words did not result in any significant differences between the languages ($F(1,17) = 1.825$, $MSE = 11.64$, $p = 0.177$, $\eta^2 = 0.097$) and a trend for Hemisphere ($F(1,17) = 3.708$, $MSE = 586.83$, $p = 0.071$, $\eta^2 = 0.179$).

Results on differences between the six language switching directions were obtained with an ANOVA (Base × Target × HS) and showed a main effect of Base ($F(2,34) = 9.09$, $MSE = 31.22$, $p = 0.001$, $\eta^2 = 0.348$), Target ($F(2,34) = 4.24$, $MSE = 29.86$, $p = 0.024$, $\eta^2 = 0.200$) and a trend for Hemisphere ($F(1,26) = 3.69$, $MSE = 1898.89$, $p = 0.072$, $\eta^2 = 0.179$). The main effect of Base showed that base languages Finnish and English and Swedish and English significantly differed from each other (mean difference Finnish – English 2.51 nAm, $SE = 0.8$, $p = 0.015$, and Swedish – English 2.20 nAm, $SE = 0.7$, $p = 0.014$) but Finnish and Swedish did not differ (mean difference Finnish – Swedish 0.31 nAm, $SE = 0.4$, $p = 1.00$), revealing that patterns where Finnish and Swedish were presented prior to switches and non-switches generated overall smaller responses than when English formed the base language. The main effect of Target revealed only a significant difference between target languages Finnish and English (mean difference Finnish – English 2.12 nAm, $SE = 0.8$, $p = 0.042$), with higher responses for Finnish. Of main interest, however, was the significant Base × Target interaction ($F(4,68) = 8.30$, $MSE = 27.33$, $p < 0.001$, $\eta^2 = 0.328$), for which Post Hoc tests revealed significant amplitude differences in the following language switching combinations: switches from English to Finnish yielded larger responses compared to Finnish non-switches (mean difference 5.09 nAm, $SE = 1.6$, $p = 0.013$); and larger responses for switches from English to Swedish compared to Swedish non-switches (mean difference 4.95, $SE = 1.4$, $p = 0.006$). [Fig. 3](#) shows the strength of N400m responses for switches from English to either Finnish or Swedish. In [Table 3](#), the average source strength in

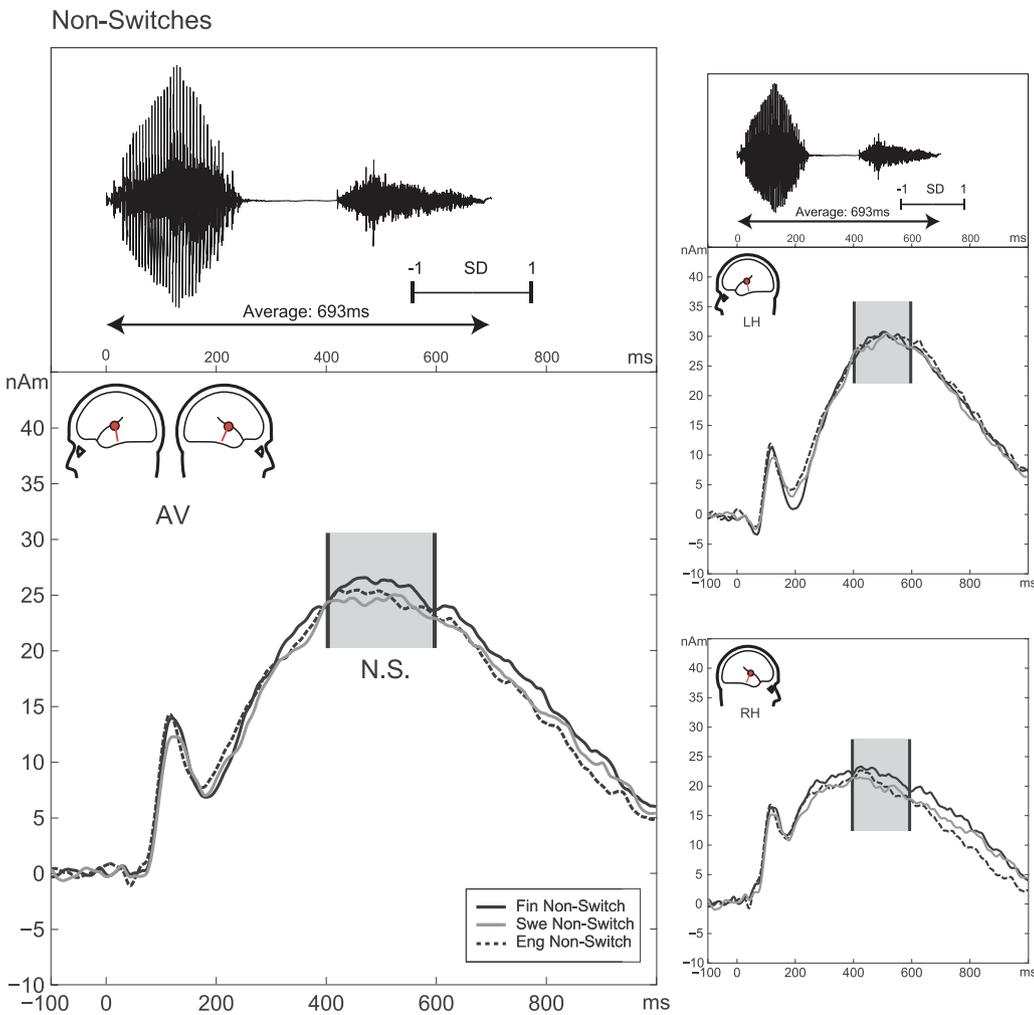


Fig. 2. Mean strength of the N400m activation to Finnish, Swedish and English non-switches, plotted as an average across left and right hemispheres, and for each hemisphere separately. Individually determined N400m sources were obtained for each individual participant, and then averaged across all participants. The speech waveform illustrates the average duration of the words in the experiment (693 ms) and their standard deviation (127 ms). The insets show the approximate location and orientation of the N400 dipole sources.

nAm is displayed for all conditions. Significant differences were also found for switches from English to Finnish and English to Swedish, as compared to English non-switches (mean difference = 6.1 nAm, SE = 1.4, $p = 0.001$, and mean difference = 4.6 nAm, SE = 1.4, $p = 0.012$, resp.) and for switches from Swedish to English compared to Swedish non-switches (mean difference = 2.8 nAm, SE = 0.9, $p = 0.014$), indicating that most of the switch patterns elicited larger responses compared to non-switches.

None of the switches from dominant to non-dominant languages resulted in increased activations (switches from Finnish to English compared to English non-switches, mean difference 0.2, SE = 0.8, $p = 1.00$; switches from Swedish to English compared to English non-switches showed a trend, mean difference 2.5, SE = 1.0, $p = 0.07$). This is further illustrated in Fig. 4.

Switches from one native language to the other did not result in significant differences either (switches from Finnish to Swedish compared to Swedish non-switches, mean difference 2.3 nAm, SE = 1.0, $p = 0.12$; switches from Swedish to Finnish compared to Finnish non-switches, mean difference 0.9 nAm, SE = 1.2 $p = 1.00$). See Fig. 5 for plotted averaged N400m source strength for switches from Finnish to Swedish and the other switching direction, Swedish to Finnish.

3.2. IFG source waveforms

In the IFG, the ANOVA (Switch \times HS) comparing switches to non-switches, showed a main effect of Switch ($F(1,17) = 13.29$, MSE = 7.03, $p = 0.017$, $\eta^2 = 0.292$), indicating that Switches elicited stronger activation in the 350–450 ms time window than non-switches did

(mean 6.0 vs. 4.3 nAm, resp.). This is illustrated in Fig. 6.

The ANOVA (Language \times HS) performed on non-switched trials resulted in a significant effect of Language ($F(2,34) = 6.819$, MSE = 18.07, $p = 0.010$, $\eta^2 = 0.286$), showing significant differences between English compared to Finnish and Swedish, but none of the other contrasts (mean difference English – Finnish 2.84 nAm, SE = 1.1, $p = 0.050$, and English – Swedish 2.3 nAm, SE = 0.7, $p = 0.008$).

Additionally, a significant interaction of Language*Hemisphere ($F(2,34) = 3.944$, MSE = 5.83, $p = 0.033$, $\eta^2 = 0.188$) was found, revealing that these differences emerged in the left hemisphere only (mean difference left HS English – Finnish 4.4 nAm, SE = 1.2, $p = 0.007$, and English – Swedish 3.3 nAm, SE = 0.7, $p = 0.001$). Fig. 7 illustrates the mean strength of the frontal activation to Finnish, Swedish and English non-switches on average, as well as in the left and right hemispheres.

The ANOVA (Base \times Target \times HS) only revealed a significant effect of Base ($F(2,34) = 4.49$, MSE = 32.01, $p = 0.020$, $\eta^2 = 0.209$), indicating differences between base language English and Finnish with significantly higher activations for English (mean difference 2.3 nAm, SE = 0.8, $p = 0.041$)

3.3. Behavioural RT data

The linear mixed effects analysis of mean reaction times (RT) between target word trials (i.e., animate words) in each of the three languages did not reveal differences ($F = 2.11$, $p = 0.12$). The one-way ANOVA on total error count also found no significant effect of Language ($F = 0.056$, $p = 0.95$). Table 4 presents the RT data and error rates for

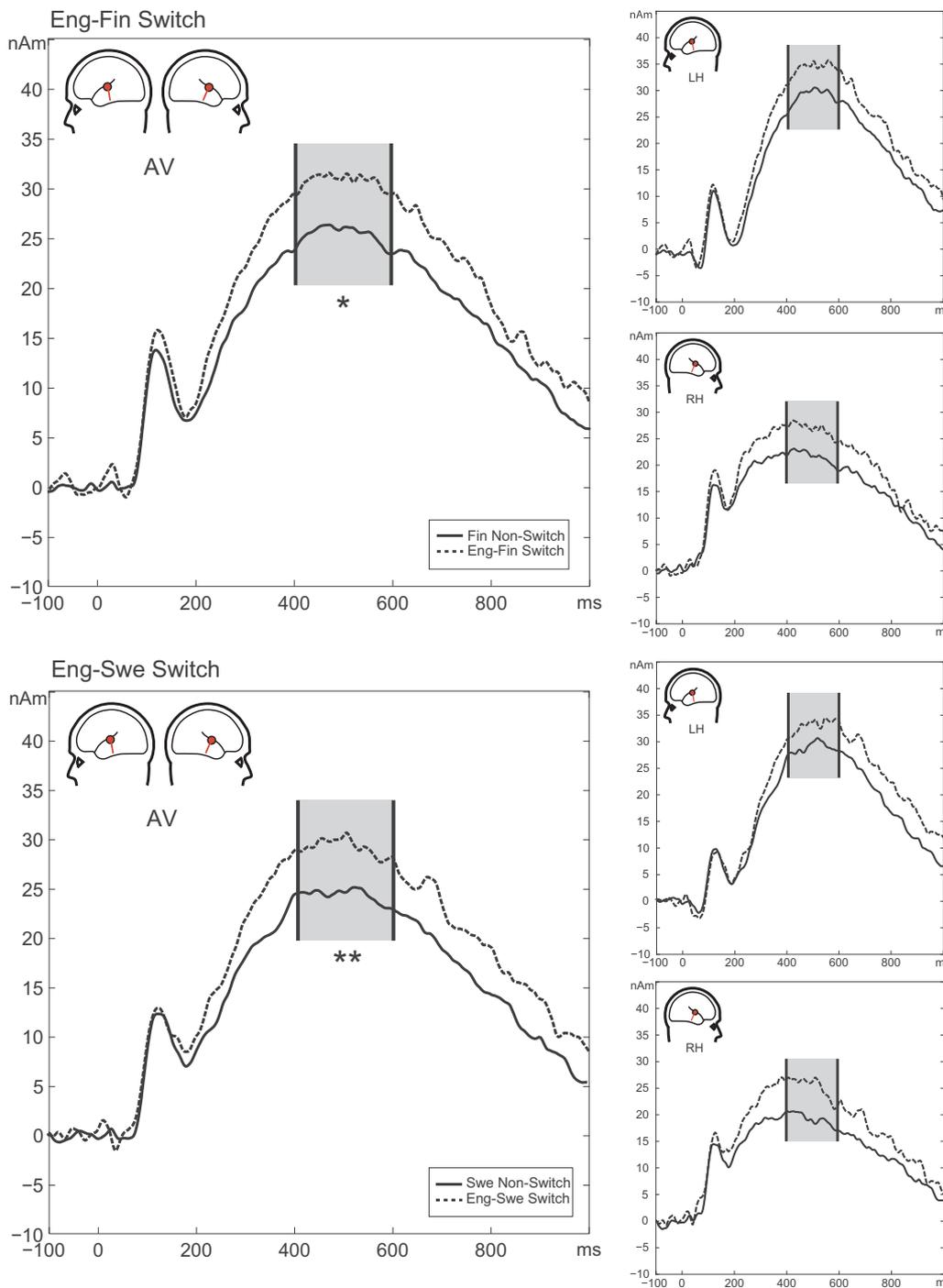


Fig. 3. Mean strength of the N400m activation to Finnish and Swedish non-switches, compared to switches from English to Finnish and switches from English to Swedish. The shaded area indicates the region with statistically significant differences. One asterisk indicates $p < 0.05$, two asterisks indicate $p < 0.01$.

each language.

4. Discussion

In the current study, we investigated language control processes between native languages acquired early in life compared to a later learned language, in which the participants were highly proficient. Trilingual speakers carried out an auditory comprehension task in three languages that frequently alternated while ongoing MEG signals were measured in real time, in order to examine language control mechanisms during language perception.

The results of this study indicate that language control processes of early acquired languages Finnish and Swedish differ from those of the later learned English. This was the case despite the fact that the

participants displayed high proficiency in all three languages, as shown by their national matriculation examination grades, current objective language test scores and performance on the experimental task. In addition, N400m responses to non-switched words did not differ across the three languages, indicating similar overall base activation levels of words in all languages. Nevertheless, switches from English to one of the two native languages resulted in increased neural activation as measured by the N400m in the bilateral Superior Temporal Gyrus (STG). Such effects were not revealed in switches between the native languages. For both switching directions in the early acquired languages, no increase in neural activation was found for switched words compared to corresponding non-switched words. According to the inhibition account, this suggests inhibition of native languages during processing of a later learned language, whereas evidence for such

Table 3
Average source strength (in nAm) for each condition, displayed separately for the left hemisphere (LH) and right hemisphere (RH).

Condition	Hemisphere	Source strength (SD) in nAm
Finnish Non-Switch	LH	29.7 (17.0)
	RH	21.4 (12.2)
Swedish Non-Switch	LH	28.7 (14.4)
	RH	19.8 (12.0)
English Non-Switch	LH	29.4 (15.5)
	RH	19.7 (11.3)
Finnish-Swedish Switch	LH	32.0 (16.5)
	RH	21.1 (13.5)
Finnish-English Switch	LH	30.1 (15.9)
	RH	19.4 (11.3)
Swedish-Finnish Switch	LH	30.1 (16.3)
	RH	22.9 (14.4)
Swedish-English Switch	LH	33.2 (18.3)
	RH	21.0 (11.9)
English-Finnish Switch	LH	34.6 (19.2)
	RH	26.8 (16.8)
English-Swedish Switch	LH	33.2 (17.7)
	RH	25.2 (15.5)

inhibition is not observed for the two native languages. Activation in the bilateral Inferior Frontal Gyrus (IFG) during the 350–450 ms time window supports this notion, as increased activation was found during English non-switch trials compared to Finnish and Swedish counterparts. This could indicate active inhibition of the native languages during the use of the later learned English. However, increased frontal activation may also be associated with a lower L2 proficiency (Perani and Abutalebi, 2005), and of decreasing left prefrontal effects as L2 proficiency increases (Abutalebi and Green, 2007), suggesting that IFG activation could indicate proficiency differences between English and the native languages. However, as pointed out above, none of measures in the current study reveals any proficiency differences. Moreover, prefrontal effects related to proficiency are usually seen in production instead of perception, and in cases of relatively large proficiency differences between L1 and L2. Alternatively, involvement of the IFG has been frequently linked to language control during language switching (Abutalebi et al., 2007; Venkatraman et al., 2006; Hosoda et al., 2012; Stein et al., 2009) and the IFG has also been suggested to be part of the cognitive control network (Miller and Cohen, 2001). Thus, in the current study, the IFG is more likely to reflect processes related to language control than indicate effortful processing of a weaker L2.

Language switch effects were observed as increased frontal responses and N400m responses in both hemispheres, more strongly in the left hemisphere. The N400(m) response is often modulated after language switches (e.g. Blanco-Elorrieta and Pykkänen, 2016; Chauncey et al., 2011; Pellikka et al., 2015) and reflects cognitive processes involved in word recognition (e.g. Helenius et al., 2009; see also a review by Hagoort, 2008). ECD modelling localised N400m switch effects in the STG bilaterally. Effects of language switching in the STG have been reported in previous studies (e.g. Pellikka et al., 2015; Hosoda et al., 2012; Luk et al., 2012). The N250 component, elicited in a similar time window as the present frontal source responses, has been found in ERP studies on language switching as well, although using the visual modality (e.g. Chauncey et al., 2008; Van der Meij et al., 2011).

There is some controversy regarding asymmetric switch costs and what they reflect (for a review, see Bobb and Wodniecka, 2013). The earlier IFG activation observed here in conjunction with the later STG activation, supports the hypothesis that the N400m, originating from the STG, reflects the resolution of prior inhibitory influences (as also proposed in Pellikka et al., 2015), by “boosting” or reactivating the lexical-semantic network of the language switched to. The involvement

of the STG in lexical-semantic processing has been widely shown in previous research (Démonet et al., 2005; Lau et al., 2008). Asymmetric switch costs have also been argued to stem from persisting activation of the weaker L2, i.e., lexical representations of L2 need additional activation and this residual activation may carry over into the next trial (Philipp et al., 2007). Theoretically, it is possible that the increased activation in the left IFG for English non-switch trials could indicate additional activation for English, as its representations may be weaker. However, IFG modulations were not found for switches to English, even though increased source strength would be expected to be seen especially there, at the moment the language comes in use and thus needs additional activity to be processed. Evidence for persisting activation was not found in the N400m response either, as the only modulations take place after switching to the two native languages. For English, the N400m responses to non-switches and switches remained constant throughout the experimental conditions, giving no support for the view that English requires additional activation during its processing.

The results of the present study supported some of our predictions. Switching from a later learned language to a native language led to an asymmetric cost in the N400m, which was expected based on models of language control that predict inhibition of stronger languages when they are not in use. This result was also in line with previous outcomes from a receptive, auditory MEG study on language switching, where increased N400m responses were seen after switching from L2 to L1 (Pellikka et al., 2015), regardless of the differences in their experimental design. For example, in the present study, language switches appeared more frequently, about every 8–10 s, whereas switches in Pellikka et al. occurred at a much slower rate. Fully tuning or “zooming” into a second language during language comprehension may take some time (Elston-Güttler and Gunter, 2008), but here, trilingual speakers’ cognitive control over their languages seems to adapt rapidly and flexibly. Asymmetrical switching cost patterns like the ones found here have been reported in the majority of previous work on language switching in behavioural production tasks (e.g. Meuter and Allport, 1999; Tarłowski et al., 2013). Visual language comprehension tasks, however, usually resulted in symmetrical costs instead (Macizo et al., 2012; Thomas and Allport, 2000; Von Studnitz and Green, 2002), whereas visual ERP studies report inconsistent modulations of the N400 component after switches (e.g., Chauncey et al., 2011; Alvarez et al., 2003). One possibility is that electrophysiological techniques are more sensitive in capturing subtle changes during ongoing word processing, which may be missed by reaction times measured at the end of the word recognition process. Also, language switching in the auditory domain may employ cognitive control differently than from switching in the visual domain. A string of individual letters can be processed in parallel and simultaneously, facilitating immediate recognition of words (Grainger and Holcomb, 2009). In speech recognition, however, the temporal unfolding of speech signals results in the partial activation of alternatives competing for activation (Dahan et al., 2001). In order to avoid interference of co-activated alternatives across languages, cognitive control may be required. Control is exerted through inhibitory influences, thus limiting the amount of phonologically similar alternatives in non-target languages. Previous research has also found language similarity to affect word processing (e.g. Dijkstra et al., 2010) and arguably, language similarity could affect language control mechanisms consequently. Here, however, we found no evidence that the language similarity between Swedish and English, both being part of the Germanic language family as opposed to Finnish, affected the switching cost patterns.

Regarding switching between the native languages, we found no switch costs (not even symmetrical ones) in the N400m and no evidence for active suppression between these languages in the IFG. The lack of switch costs in these switch directions was unexpected. As strong languages are hypothesised to pose greater interference to the other languages (Green, 1998), our prediction was to find modulated N400m responses for these types of switches as well. Instead, switches elicited

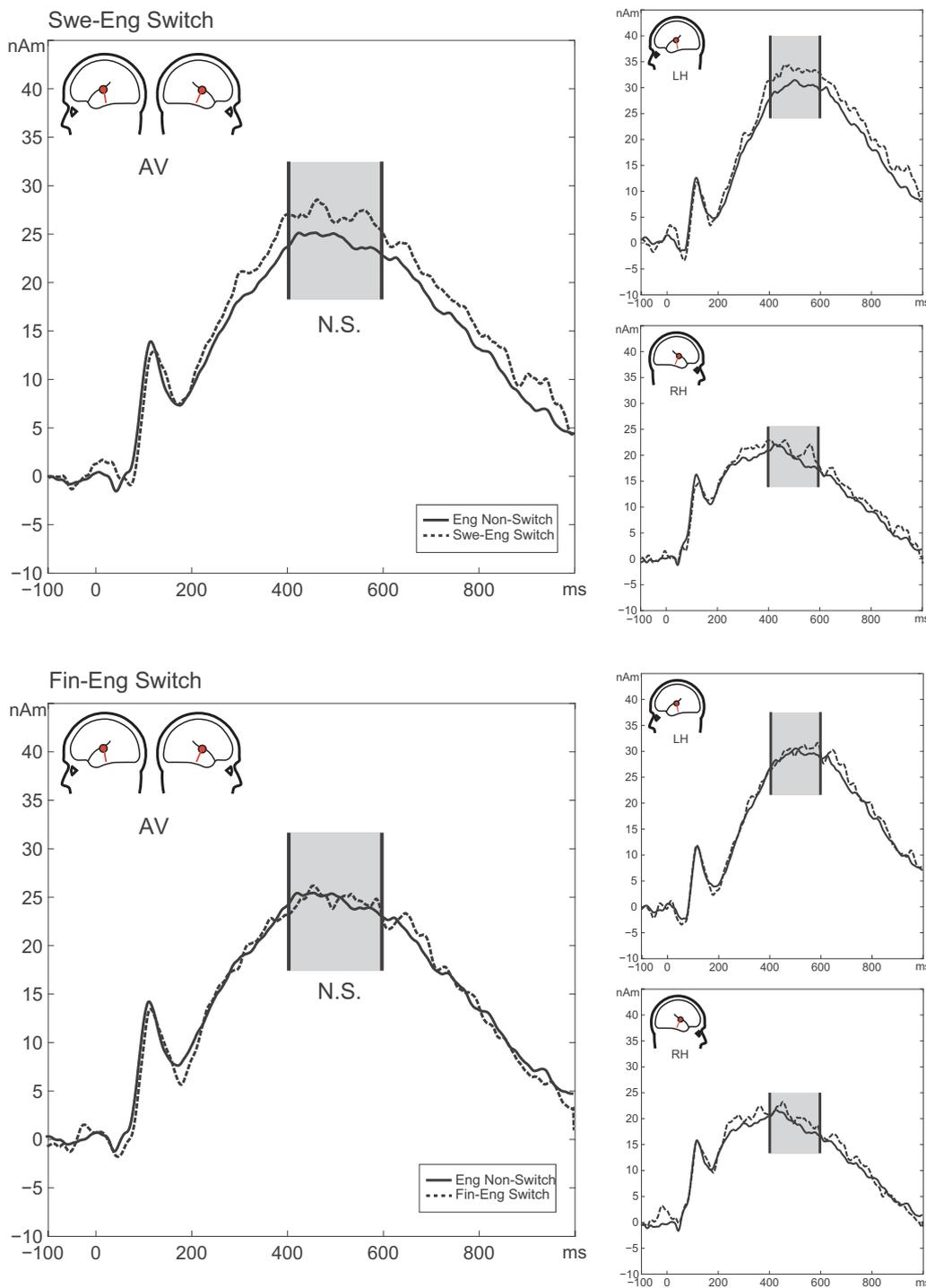


Fig. 4. Mean strength of the N400m activation to English non-switches compared to switches from Finnish to English and switches from Swedish to English. Separate plots for the average across left and right hemispheres and for the left and right hemisphere.

similar N400m responses as non-switches did, suggesting that switches to the native languages do not require the lexical-semantic system to reactivate because it is already active and readily accessible. This result indicates that the organization of two early learned languages differs from that of a later learned language, or that the control processes for these native languages are more effective.

Our results show evidence for inhibitory control over the weaker language. Namely, the asymmetric costs for switches between the later learned English and the natives language were conform predictions based on the Inhibitory Control model (Green, 1998), even though this model principally regards language control in language production. The BIMOLA (Grosjean, 1988; Léwy and Grosjean, 2008) and BIA+ (van Heuven and Dijkstra, 2010) are more specifically targeted at language

perception. The assumed non-selectivity in the BIA+ eliminates the role of top-down control, although it allows surrounding linguistic and nonlinguistic context to affect language access. BIA+ furthermore assumes switch costs to stem from an effort needed to switch between language tasks schemas, needed to perform a task in a particular language. Due to the nature of the current experimental task, it was not necessary to identify language membership to perform the task. Thus, the participants did not require to switch between different task schemas and hence, switch costs between the languages would not be predicted in this model. BIMOLA seems more apt to explain the asymmetric costs, for it suggests top-down control to affect inhibitory and excitatory influences based on the linguistic input. A similar explanation, albeit in the visual domain, could be offered by the BIA

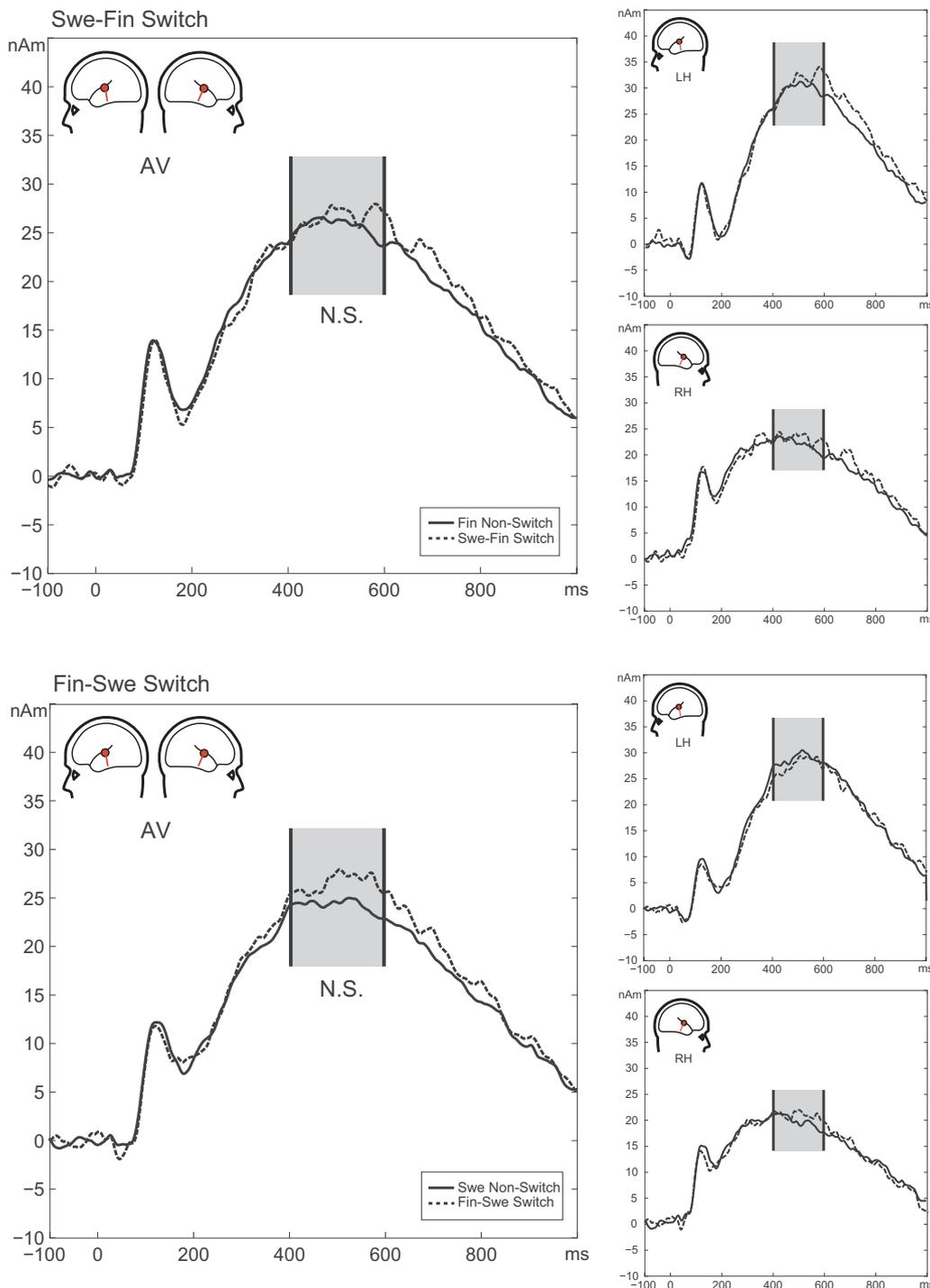


Fig. 5. Mean strength of the N400m activation in the left and right hemispheres to Finnish and Swedish non-switches, compared to switches from Swedish to Finnish and switches from Finnish to Swedish, respectively.

(Dijkstra and Van Heuven, 2002), the predecessor of BIA +.

Our results on switching between the two native dominant languages were however not fully in line with predictions made by BIA, BIMOLA nor the IC model. An inhibitory account on switching between native languages would assume that their high base activation would require extra inhibition to overcome each other's interference. Similar reasoning was put forward by Gollan and Ferreira (2009), who hypothesised that highly proficient bilinguals may apply equal inhibition to both languages. Following this, we predicted increased N400m responses for switches between native languages, but instead, the present study did not reveal differences compared to non-switches, and no evidence for such inhibitory processes.

Our results therefore show that control mechanisms involved in the

management of native languages differ from those needed for later-learned languages. It has been previously suggested that control mechanisms during language production are affected by robustness of language in terms of language use and strength of lexical representations, with more efficient language selection processes for languages that are more robust (Costa et al., 2006). As proficiency was largely controlled in the present study, driving factors that modulate language control could be AoA, language exposure across the lifespan, and frequency of language usage, based on participant characteristics after careful selection of early bilinguals with specific language backgrounds. The early (simultaneous) acquisition of both languages and an upbringing in an environment characterised by frequent language switching could have led to language switching becoming more

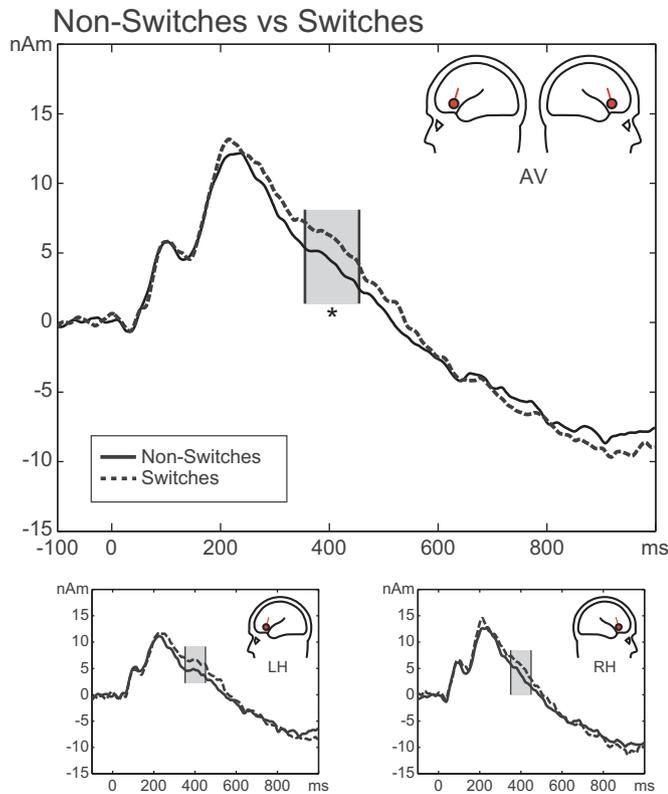


Fig. 6. Mean strength of the frontal activation in the left and right hemispheres for non-switch trials compared to an average of all switch trials. The insets show the approximate location and orientation of the frontal dipole sources.

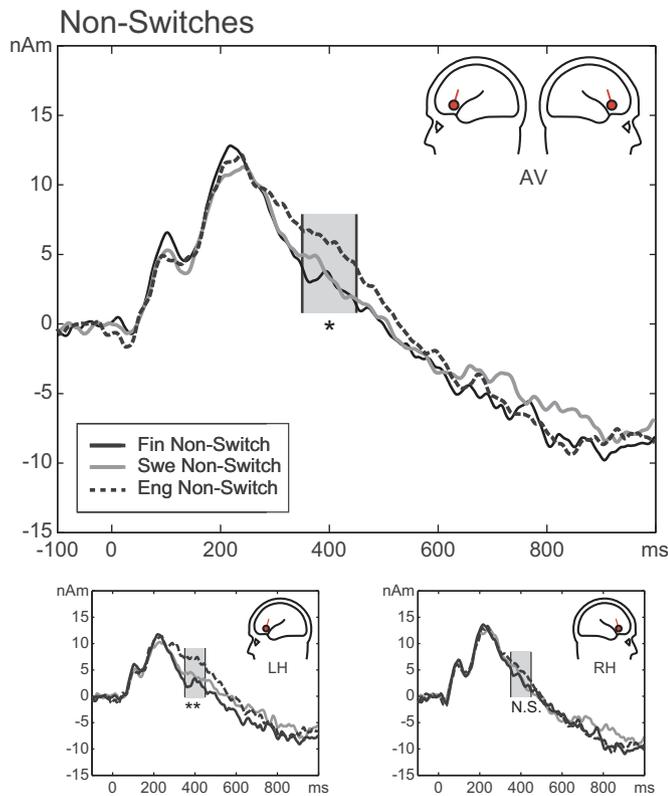


Fig. 7. Mean strength of the frontal activation in the left and right hemispheres to all non-switch trials.

Table 4

Mean reaction times (RT) in milliseconds and error rates (absolute count) for each of the three languages. Standard deviations are reported between brackets (SD).

	RT in ms (SD)	Errors (SD)
Finnish	993 (195.7)	11.2 (7.6)
Swedish	994 (195.3)	11.9 (7.9)
English	1002 (191.3)	11.9 (5.9)

automatised in these trilinguals. In turn, this could have led to the modulation and development of underlying language control mechanisms for their native languages specifically. When language processing becomes more automatic, less dependency on prefrontal support may be needed (Perani et al., 2003).

A previous ERP study found smaller switch costs for bilinguals with more experience in the target language, indicated by a modulated Late Positivity Complex (Moreno et al., 2002), which supports this view. All participants in the current study grew up in a bilingual environment. For 13 participants (72%) the mother spoke another language than the father did. Four participants (22%) used only Swedish in the early home situation and one participant used only Finnish in the early home situation (although attending a Swedish primary school). Language use throughout childhood and adolescence was deemed more or less equally balanced for all participants, and reported values of current language usage (42% for Swedish, 40% for Finnish and 18% for English) indicated that this trend remained fairly stable. Another study also showed evidence that language-switching experience plays a key role regarding the bilingual advantage in cognitive control processes, rather than high second-language proficiency (Verreyt et al., 2016). In the current study, we limited the role of language proficiency, by including only participants with a high-proficient command of English due to its regular use. This leaves AoA and language usage as strong candidates to explain the differential control mechanisms observed here, and both of these factors have been attributed to affect patterns of brain activation in bilinguals in previous research (e.g., Perani et al., 2003). Short-term increase of language exposure to L1 results in stronger activation of the IFG during L2 processing in early bilinguals (Tu et al., 2015), which is in line with findings in the current study. Earlier research has further indicated that AoA affects language processing greatly, such that words learned at a different age are represented differently in the brain (Fiebach et al., 2003). In the current study, it was not possible to investigate the role of each of these factors in isolation. The exact contributions of AoA and language use on cognitive control remain to be resolved in future studies.

5. Conclusions

The current study revealed that language control mechanisms for early acquired languages differ from those of a later learned language. We also show that language control processes are recruited during auditory language comprehension, i.e., even during a receptive task. During incoming speech input, inhibitory control of non-target languages seems to occur when switching from a native language to a later learned language, but not for switches between native languages. Automatisations of language switching, due to the long experience of switching between early acquired languages, may underlie these differences.

Acknowledgements

This study was supported by PsyCo Graduate School (first author), the Academy of Finland (Grants 137511 and 288880), the Lundbeck Foundation (Grant 2013-12951), KONE Foundation, University of Helsinki 3-year funds (last author) and the Emil Aaltonen Foundation (last author). We would like to express our gratitude to all of our

participants, and to Camilla Hannuksela for her help with the recordings of the stimuli. We would further like to thank Lena Henke for her assistance during the re-analysis of the neural sources.

Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at <http://dx.doi.org/10.1016/j.neuropsychologia.2017.11.016>.

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