ERP correlates of executive control during repeated language switching*

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A key aspect of higher cognitive function is the ability to switch rapidly and efficiently between alternative modes of response where this is appropriate behaviourally. Such suppression appears to be highly dependent upon the integrity of the prefrontal cortex, yet other cortical areas are likely to be necessary to implement response switching. Language switching in bilingual speakers is a clear example of a task in which response switching is required. Functional brain imaging studies have demonstrated parietal cortex activation during repeated language switching within a translation task. Here we used event-related dense-sensor EEG recording techniques to examine the time course of language switching during a visually cued naming task in which bilingual participants named digits in either their first or second language. Switch-related modulation of ERP components was evident over parietal and frontal cortices, and in the latter case showed an asymmetry across first and second languages. Correspondence with a frontal ERP component found when suppressing manual responding in a Go/No-Go reaction time task may imply that similar inhibitory mechanisms are involved in both response suppression and language switching.

The selection and execution of action involves translating sensory information into appropriate motor command signals (Andersen, Snyder, Bradley and Xing, 1997; Jackson and Husain, 1996). Physiological investigations in monkeys (Snyder, Batista and Andersen, 1997), together with brain-imaging studies in humans (Clower, Hoffman, Votaw, Faber, Woods and Alexander, 1996), confirm the importance of cortical networks linking posterior parietal areas with premotor regions of the frontal cortex to this transformation process. While evolution has made these fronto-parietal visuomotor transformations highly efficient and largely automatic (L'hermitte, 1983), a key aspect of higher cortical function is the ability to actively suppress habitual responses (Drewe, 1974), and to switch rapidly and efficiently between alternative forms of response where this is behaviourally appropriate. Here we report a study of language switching in bilingual speakers which offers a clear and naturally occurring example of response switching.

Electrophysiological studies in non-human primates (Sasaki, Gemba and Tsujimoto, 1989) and in humans (Jackson, Jackson and Roberts, 1999), together with neuropsychological (L'hermitte, 1983; Rogers, Sahakian, Hodges, Polkey, Kennard and Robbins, 1998), and functional brain-imaging studies in humans (Konishi et al., 1998; Konishi, Nakajima, Uchida, Kikyo, Kameyama and Miyashita, 1999), suggest that this *selective control* function is highly dependent upon the intact operation of the prefrontal cortex. The nature of these selective control mechanisms and their anatomical basis are currently poorly understood, and it remains to be clarified whether other brain regions have an important role to play in implementing the rapid and efficient switching of behavioural responses.

Response switching deficits associated with frontal lobe damage or disease have frequently been investigated using neuropsychological tests such as the Wisconsin Card Sorting Test (WCST) (Milner, 1963), and recent attempts to localise the anatomical basis for set-shifting using brain-imaging techniques (fMRI) have also made use of the WCST (Konishi et al. 1998). Of particular relevance to the current study is the recent finding that the anatomical region that is activated transiently during cognitive set-shifting during performance of the WCST – the inferior frontal sulcus of the right hemisphere, is spatially overlapping with the region of activation associated with inhibiting or suppressing a response during a Go/No-Go task (Konishi et al. 1999). These results have been interpreted as evidence that the right

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inferior prefrontal area is commonly involved in both the suppression of motor responses and in response switching during performance of the WCST (Konishi et al. 1999).

Unfortunately, interpreting the results of such studies is made difficult by the complex nature of the WCST, which involves many cognitive processes: rule-induction; the need to maintain current task-relevant information "on-line"; and the need to actively suppress previously relevant "rules" when these are no longer appropriate. For this reason, other tasks have been adopted to investigate task/set-switching (Meuter, 1994; Meuter and Allport, 1999).

We investigated the behavioural costs and functional brain-imaging correlates of response switching using a digit naming task in which bilingual speakers were required to switch between languages based upon an arbitrary learned stimulus–response (S–R) mapping (i.e., a colour cue) (Meuter, 1994; Meuter and Allport, 1999). The selective control problems posed by task switching are exemplified in the case of the bilingual speaker, who, during the course of a single conversation, may need to switch back and forth between languages depending upon the preferred language of the listener(s). Models of executive control, when applied to the language switching task, have posited that selective lexical access is based upon the active inhibition of the non-target language (Green, 1986, 1998a, b). Consistent with this view, previous behavioural studies of language switching in bilinguals demonstrate that there is a significant and measurable response time cost associated with switching from one language to another, and that this cost is observed even when switching is entirely predictable (Meuter, 1994; Meuter and Allport, 1999). We chose therefore to use the language switching task as a means for investigating the brain mechanisms underlying response switching.

Experiment outline

In the current study, bilingual speakers performed a speeded digit naming task in which they were required to repeatedly switch between their first and second languages. The language used to name the digit on each trial was signaled by an arbitrary visual cue; in this case the colour of the digit (Figure 1). Trials were categorised into three groups for each language: *pure* language trials in which participants completed a whole block of trials in a single language; *non-switch* trials in which participants responded in the same language as that in which they had responded on the previous trial; and *switch* trials in which the language used for the current trial *was different* to that used on the previous trial.

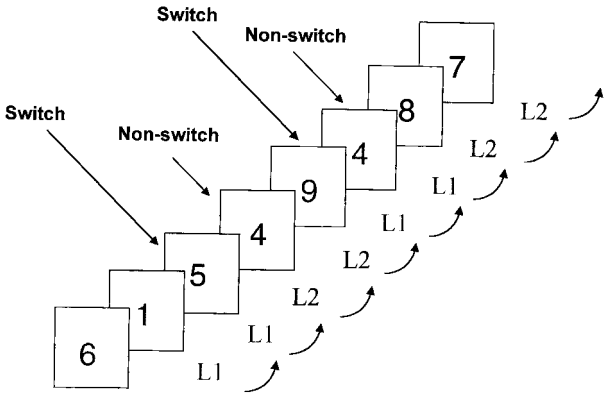


Figure 1. Illustration of the task. Single digits (1–8) were presented singly at the centre of the computer screen, and participants were instructed to name each digit as quickly as possible.

In previous behavioural studies of digit naming (e.g., Meuter, 1994) participants responded by making a speeded verbal response as soon as they identified the visual stimulus (digits). Whilst this procedure yields excellent RT data, it presents a problem if participants execute a verbal response during the period when EEG is being recorded from the scalp. This is because scalp EEG may become contaminated by muscle EMG associated with jaw and head movement. We chose to overcome this problem by having participants execute their verbal response at the *offset* of the visual stimulus rather than its onset. Furthermore, we designed the study to contain a mixture of long (1000 ms) and short (250 ms) duration stimuli so that we might obtain reliable RT data from short duration trials and reliable, artefact-free, ERPs from the long duration trials.

Method

Participants

Twenty-six neurologically normal native English speakers (age range = 18–53 years) performed a speeded digit naming task in which the language in which they should respond was signalled by a visual cue (the colour of the digit). Participants were recruited according to the criteria that English was their first language (L1) and that they felt able to name the digits 1 to 8 fluently in a second language (L2). Data from six participants were excluded from the analysis after artefact rejection (see ERP analyses); of the remaining 20 participants, the second languages used were: French (13 participants), German (3 participants), Spanish (2 participants), Mandarin (1 participant) and Urdu (1 participant).

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The second language was acquired by most participants at secondary school age (13–18 years), by two participants during infancy and by two participants during adulthood. Verbal proficiency in the second language was self-rated on a seven-point scale (0 = very poor; 7 = highly proficient): average proficiency in L2 was 3.3 (range 1–7) compared with 6.5 (range 4–7) in L1.

Procedure

Participants viewed stimuli projected onto a screen from a distance of 2.2 m. Each trial began with a central fixation mark that was replaced by the first stimulus after 1500 ms. Stimuli were single digits (1–8), presented one at a time in the centre of the screen for either 250 ms (short duration) or 1000 ms (long duration). The visual angle of stimuli measured 2.9° vertically and between 0.8°–1.8° horizontally (depending on the particular digit). Digits were coloured, the colour indicating to participants in which language to name the digit. Each participant was assigned a pair of colours – red/green or yellow/blue – within which one colour indicated the first language, and the other colour indicated the second language. (Note, across the experiment, the assignment of digit colour to responding language was fully counterbalanced.) Participants were instructed to wait until the digit was removed from the screen (i.e., at stimulus offset) before naming the digit as quickly as possible. As noted above, this procedure was adopted in order to prevent the ERP recording being affected by tongue and muscle EMG activity associated with speech production. For this reason reaction times were based solely upon *short duration* trials, whereas ERP analysis was carried out only for *long duration* trials. The participant's response was detected by a microphone which triggered an electronic voice key; the experimenter recorded errors during the testing session so that error trials could later be excluded from the analysis. Reaction times were determined from the offset of the visual stimulus (digit) until the voice onset. After the participant's response, or 1500 ms in the absence of a response, the fixation mark was redisplayed prior to the next trial. During the experimental block, trials followed a fully predictable sequence, with two consecutive trials in each language and a language switch required every second trial (see Figure 1).

The experimental block consisted of 512 *switch* and *non-switch* trials (i.e., 64 long and 64 short onset trials for each type of trial – L1 switch, L1 non-switch, L2 switch, L2 non-switch); a 15-second break was given after every 64th trial, after which the participant pressed a button to continue with the next set of 64 trials. Prior to commencing the experimental trials, two blocks of pure language (i.e., participants responded in a single language for the entire block) trials were presented, each consisting of 128 trials. The first block of control trials required digit naming exclusively in English (a *Pure L1* block). The second block of trials required responses only in the participant's second language (a *Pure L2* block).

ERP analyses

High density event-related electrical potentials (ERPs) were recorded from each participant using a 128-channel geodesic sensor net coupled to a high input impedance amplifier (Tucker, Liotti, Potts, Russell and Posner, 1994). EEG was continuously recorded and digitised at 500 Hz. Wherever possible, impedances were reduced to $< 50\ K\Omega$ prior to recording; where this level could not be attained by adjusting or wetting the sensor with electrolyte solution, and where this led to noisy recordings, the sensor was excluded before analysis (see below). The continuous EEG was then segmented into one-second epochs time-locked to the onset of each visual stimulus, commencing 100 ms prior to stimulus onset. Trials where the participant's response was incorrect, absent or occurred before stimulus offset, and trials containing eye movement artefacts (i.e., an EOG channel difference greater than 70 μV); or, trials containing more than ten bad channels (channels with voltage amplitudes over 200 μV or a change in amplitude between adjacent samples of more than 100 μV) were rejected from the dataset prior to averaging. Channels that were bad for more than 25% of trials for a given participant were excluded from all analyses. Six participants' data showed unacceptably high numbers of bad channels, five due to probable sweating artefacts and the sixth to prolonged facial muscle activity; these were rejected from the subsequent analyses. Four or fewer channels were rejected for the remaining 20 participants whose data were then analysed further. The average number of trials retained out of the total of 64 for each participant per condition was 56 (range 40–64). ERPs were transformed using an average reference transform, and low-pass filtered with a cut-off frequency of 45 Hz. The epoch was baseline-corrected using data from the 100 ms prior to stimulus onset.

Results

Behavioural data

Mean response times (RTs) for each type of trial and for each language were calculated for each individual

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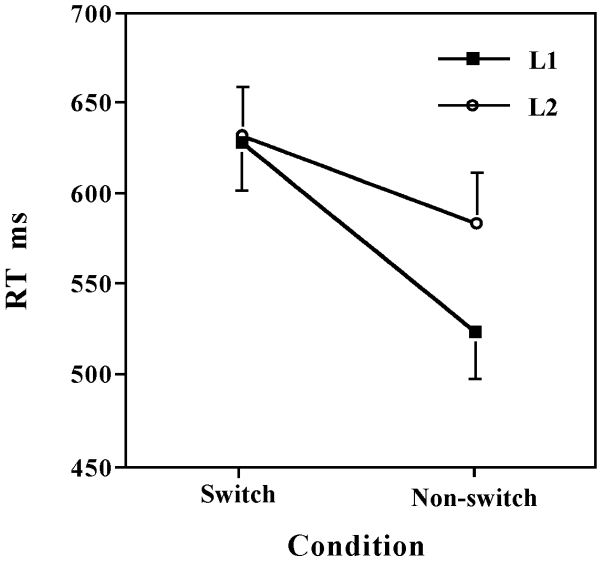


Figure 2. Mean response times for switch and non-switch trials for L1 and L2. Error bars indicate the standard errors.

participant and entered into a 2 x 3 repeated-measures analysis of variance (ANOVA). For brevity only the data from switch and non-switch trials will be considered. Relevant means are presented in Figure 2.

The ANOVA confirmed that participants' RTs were slower overall when naming digits in their second (L2) language ($F[1,19] = 6.8$, $p < 0.025$), and that there was a significant main effect of Trial Type (means [standard deviation]: non-switch = 557 [123] ms; switch = 631 [118] ms; $F[2,38] = 36.8$, $p < 0.0001$). The ANOVA also revealed a significant Language x Trial Type interaction effect ($F[2,38] = 9.5$, $p < 0.002$). The simple effects of this interaction revealed that for both L1 and L2, RTs were slowed for switch trials compared to non-switch trials (minimum $F[1,19] = 20.1$, $p < 0.0005$). However, while L1 and L2 RTs were significantly different for non-switch trials ($F[1,19] = 33.7$, $p < 0.0001$), L1 and L2 RTs did *not* differ for switch trials ($F < 1$). It is important to note that these data do not replicate exactly those reported by Meuter and Allport (1999). Specifically, we do not obtain the cross-over interaction pattern (i.e., L1 RTs are longer than L2 RTs for switch trials but shorter than L2 RTs for non-switch trials) obtained in that study. Instead we find that RTs when switching from L2 to L1 do not differ from those observed when switching from L1 to L2.[1]

[1] It should be noted that we obtained this same pattern of RTs in a previous behavioural study of digit naming in 20 English–Welsh bilingual speakers.

ERP analyses

In the interests of brevity we focus here only on differences in the ERP between switch and non-switch conditions and how these differences vary across L1 and L2. More detailed analyses of the complete dataset will be reported elsewhere. Furthermore, as preliminary analyses reveal many switch vs. non-switch differences at multiple electrode sites across the scalp, we restrict ourselves to discussing those effects that are of most theoretical relevance.

Early fronto-central (N50) effect

Preliminary analyses were carried out to examine the time course of differences between switch and non-switch trials across the entire scalp using t-tests. These analyses revealed that, as early as 50 ms after stimulus onset, there was a cluster of electrodes located over the left fronto-central region of the scalp that differed significantly for switch and non-switch conditions. Figure 3a shows the distribution of sensors with statistically significant t-values at 50 ms after stimulus onset and Figure 3b shows this distribution at +70 ms. Figure 4 shows the entire time course for switch vs. non-switch conditions (collapsed across languages) for sensors within this left fronto-central quadrant. The grey line shows the peak of this difference at +60 ms. Using the method suggested by Rugg and colleagues (Rugg, Doyle and Wells, 1995) – ten consecutive t-test samples which exceed the 0.05 significance level – it can be seen that there is a significant negative deflection in the ERP for switch trials compared to non-switch trials. One possible explanation for this effect is that it represents detection of a physical change in the visual stimulus.[2] That is, in the non-switch trials the colour of the digit was identical to that presented on the previous trial. By contrast, during switch trials the colour of the digit changed from that presented on the previous trial.

Modulation of the fronto-central N320

The next analyses were directly predicated upon the suggestion, outlined earlier, that response switching and the response suppression observed in a Go/No-

[2] This interpretation was confirmed in a control condition. Prior to completing the experimental task, a subset of 13 participants carried out the digit-naming task entirely in their first language. Digits were presented in two different colours, however, the colour was irrelevant to the task and participants were instructed to ignore the colour change. Under these circumstances a similar difference between switch (colour change) and non-switch (no colour change) was again observed at +60 ms suggesting therefore that this effect is unlikely to reflect mechanisms associated with response or language switching.

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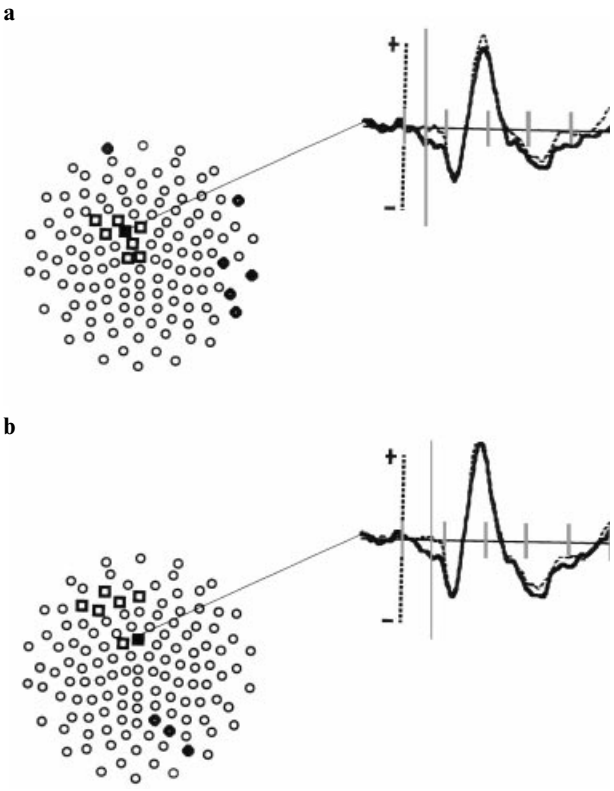


Figure 3.
3a The distribution of sensors with statistically significant t-values at 50 ms after stimulus onset. The associated waveform shows the time course of the ERP recorded at the sensor with the largest t-value. The thick waveform represents switch trials and the thin waveform represents non-switch trials. Waveforms are presented with positive values upward. The broken vertical line represents a change of 5 μV from −2.5 μV to 2.5 μV. The solid horizontal line represents a time line of 1000 ms from −100 ms to +900 ms with stimulus onset occurring at 0 ms. The grey vertical line represents the time at which the topographic distribution of t-values was obtained.
3b The distribution of sensors with statistically significant t-values at +70 ms.

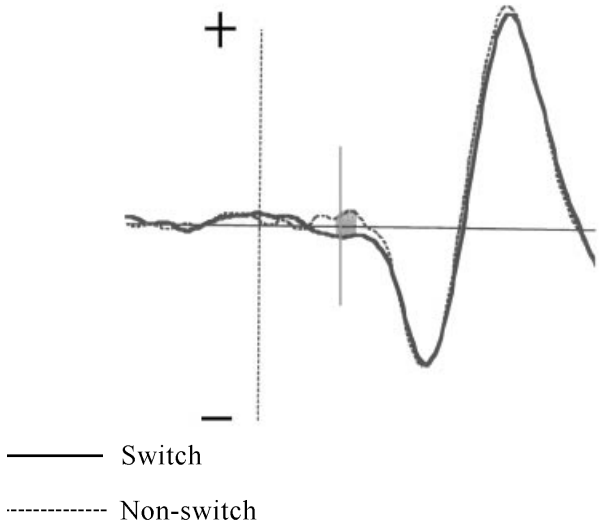


Figure 4. Switch compared to non-switch ERP waveforms (collapsed across languages) recorded at sensors within the left fronto-central quadrant. The broken vertical line represents a change of 5 μV ranging from −2.5 μV to 2.5 μV. The solid horizontal line represents a time line of 1000 ms from −100 ms to +900 ms with stimulus onset occurring at 0 ms. The blocks of grey represent time points with statistically significant differences (t-values) between conditions. Note that there is an early (+50 ms, statistically significant, negative deflection in the ERP for switch trials compared to non-switch trials. The grey line shows the peak of this difference at +60 ms.

Go task share a common neural substrate (Konishi et al., 1999). We have previously shown that the decision to suppress a response on a No-Go trial in a visual Go/No-Go paradigm is associated with an enhanced negative deflection in the ERP at frontal electrode sites (Fz) approximately 280 ms after stimulus onset (the frontal N2). We therefore explicitly investigated whether a similar increased negativity was observed at frontal electrode locations for switch trials. Figure 5 shows the time course of the ERP for switch and non-switch conditions at sensors located within the left fronto-central quadrant reported above. T-tests performed at each time sample revealed that there was a significant increase in the magnitude of the switch-related negativity compared to non-switch trials, and that this increase in ERP negativity began at a similar point in time [+310 ms] to the No-Go potential (frontal N2) which we have reported previously [+283 ms] (Jackson et al., 1999). This result would appear to provide support for the suggestion, based upon functional brain imaging data, that response suppression and response switching share a similar neural substrate. That is, we find an increased negativity in the frontal N2 for switch trials at a similar point in time to where we have previously shown an increased negativity during No-Go trials. In order to examine further the similarities between this effect and the increased N2 negativity obtained in our previous Go/No-Go study, we examined the spatial distribution of electrical activity over the scalp. This was carried out by performing an Independent Components Analysis (ICA) using the Infomax algorithm (Bell and Sejnowski, 1995) for each dataset in turn. ICA performs a blind separation of the ERP into a number of temporally independent components each with a fixed spatial topography. Note that ICA does not provide a solution to the inverse problem and that it

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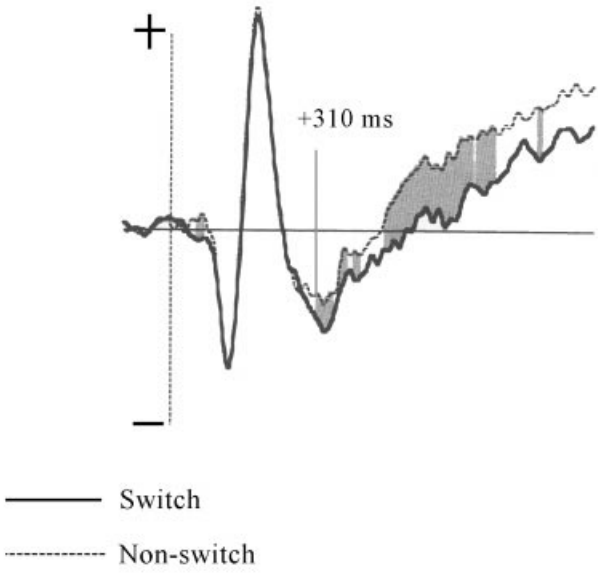


Figure 5. The time course of the ERP for switch and non-switch conditions (collapsed across languages) at sensors located within the left fronto-central quadrant. The broken vertical line represents a change of 5 μV ranging from −2.5 μV to 2.5 μV. The solid horizontal line represents a time line of 1000 ms from −100 ms to +900 ms with stimulus onset occurring at 0 ms. Blocks of grey represent time points with statistically significant differences (t-values) between conditions. Note that there is a statistically significant, negative deflection in the ERP for switch trials compared to non-switch trials which begins at 310 ms after stimulus onset (depicted by the grey line).

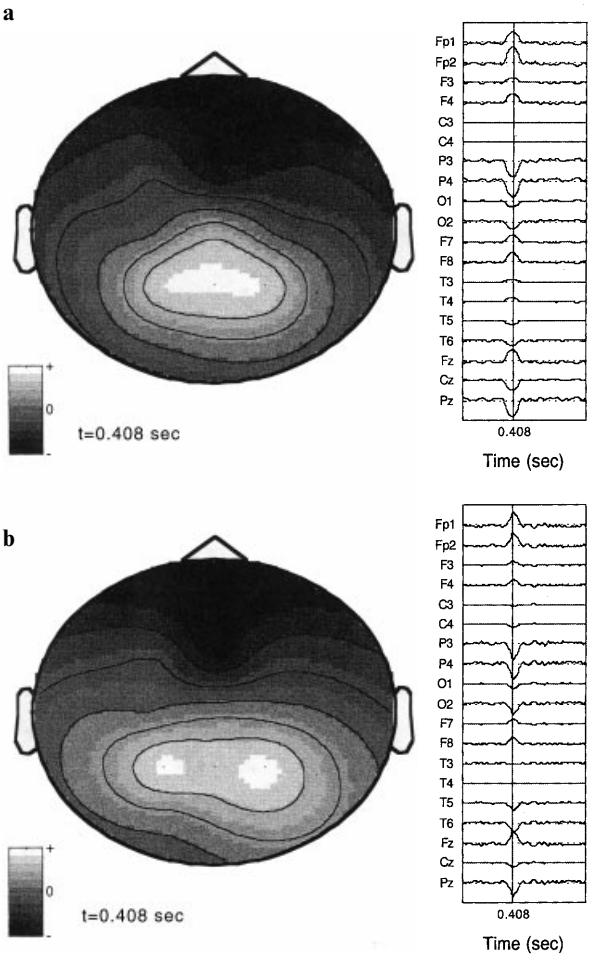


Figure 6. Results of the Independent Component Analysis (ICA).
6a The spatial topography of the ICA component associated with the frontal N2 ERP deflection obtained on No-Go trials (Jackson et al., 1999) together with a plot of the time course of the activation of this component at important electrode sites across the scalp.
6b The spatial topography of the ICA component associated with switch N2 ERP deflection together with the associated time course of this component's activation across the scalp.

is not a method for localising the neural sources of ERP signals. Instead, ICA provides a decomposition of the data into a set of ERP "components" in which the time course of each ICA component is statistically independent from all other components and where each is associated with a single, fixed, spatial topography (see Makeig et al., 1999 for further details of the assumptions underlying ICA and its application to the analysis of EEG signals). For each dataset a single ICA component was identified which had a single peak of maximum activation occurring within the time course of the N2 negative deflection and which showed different levels of activation between experimental conditions (i.e., Go vs. No-Go and Switch vs. Non-switch). Figure 6a shows the spatial topography of the ICA component associated with the frontal N2 ERP deflection obtained on NoGo trials together with a plot of the time course of the activation of this component at important electrode sites across the scalp. Figure 6b shows the spatial topography of the ICA component associated with the Switch N2 ERP deflection together with the associated time course of this component's activation across the scalp. Inspection of this figure clearly demonstrates that both ICA components have a highly similar spatial distribution; consistent with the suggestion that response suppression and response switching may depend on the same neural substrate.

Is the frontal N2 effect obtained here different across L1 and L2? One important difference between the current task and the Go/No-Go task is that language proficiency is asymmetric across L1 and L2. Another is that control of access to L1 and L2 is thought to be based upon mutual inhibition between competing lexicons (Green, 1998a). This predicts that

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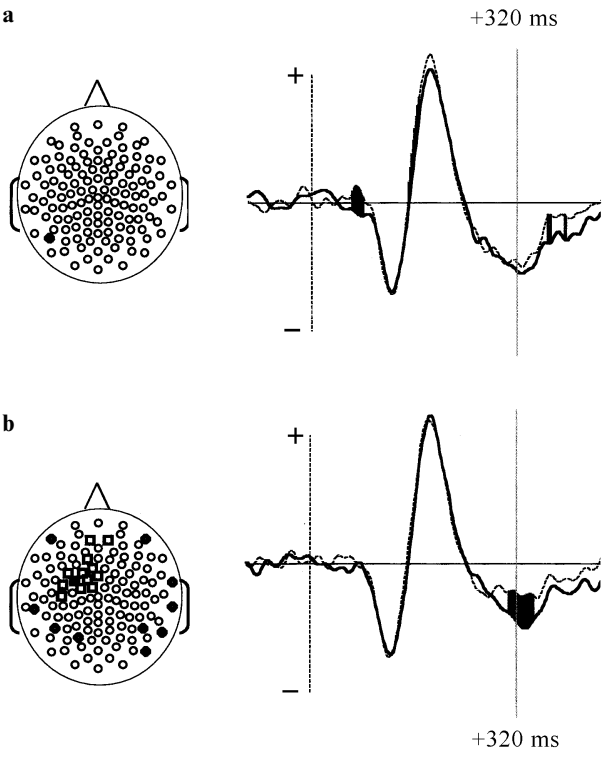


Figure 7. 7a The distribution of sensors with statistically significant t-values at 320 ms after stimulus onset (the peak of the N2 component) for L1. Statistically significant t-values are indicated by □ or ● symbols. The associated waveform shows the time course of the ERP recorded at left fronto-central sensors. The thick waveform represents switch trials and the thin waveform represents non-switch trials. The broken vertical line represents a change of 5 μV from −2.5 μV to 2.5 μV. The solid horizontal line represents a time line of 500 ms from −100 ms to +400 ms with stimulus onset occurring at 0 ms. 7b The distribution of sensors with statistically significant t-values at 320 ms after stimulus onset for L2. Statistically significant t-values are indicated by □ or ● symbols. The associated waveform shows the time course of the ERP recorded at left fronto-central sensors. The thick waveform represents switch trials and the thin waveform represents non-switch trials. The broken vertical line represents a change of 5 μV from −2.5 μV to 2.5 μV. The solid horizontal line represents a time line of 500 ms from −100 ms to +400 ms with stimulus onset occurring at 0 ms.

accessing L1 should lead to inhibition of L2 and vice versa. Furthermore, this inhibition should be asymmetric; with greater inhibition of L1 (the pre-potent language response) being required when accessing L2 than when accessing L1. In the current task, if the switch-related modulation of the frontal N2 is associated with response suppression during language switching, then we would expect to see an increased modulation (switch–non-switch difference) of this negativity on L2 trials (when the L1 response needs to be suppressed) compared with L1 trials. This prediction was confirmed in the current study. Figure 7a shows the distribution of sensors with statistically significantly t-values for the L1 switch (from L2) vs. L1 non-switch trials at 320 ms (peak of the frontal N2 negativity) after stimulus onset, and the entire time course for L1 switch vs. L1 non-switch conditions for sensors located within the left fronto-central quadrant (see Figure 7b). As can be clearly seen from Figure 7b, neither the topographic distribution of t-values nor the time plot illustrating the N2 component, provides support for a statistically significant difference in the magnitude of the N2 component. By contrast, this is clearly not the case for L2. Figure 7b shows the distribution of sensors with statistically significantly t-values for the L2 switch (i.e., from L1) vs. L2 non-switch trials at +320 ms, and the time course for L2 switch vs. L2 non-switch conditions for sensors within the same left fronto-central quadrant. Inspection of this figure shows a cluster of significant t-values located within the left fronto-central region associated with an increased negativity of the frontal N2 component for switch trials compared to non-switch trials. Examination of the time course of this effect revealed that L2 switch and L2 non-switch trials became significantly different from one another 300 ms after the onset of the stimulus and remained significantly different on consecutive samples for a period of 50 ms.

In summary, we tested the suggestion that response switching and the response suppression observed in a Go/No-Go task share a common neural substrate (Konishi et al., 1999) by explicitly examining the time course and magnitude of the frontal N2 component of the ERP which we have previously reported is associated with response suppression in the Go/No-Go task. We showed that the N2 component (+320 ms) recorded over the left fronto-central region of the scalp was significantly more negative on switch trials compared to non-switch trials. In addition we showed, using Independent Components Analysis, that the spatial distribution of the ICA component associated with the frontal N2 deflection in the ERP was highly similar for both the Go/No-Go dataset and the language-switching dataset. Finally, we demonstrated that the frontal N2 effect varied according to the direction of the language switch; the effect was significant when switching from L1 to L2 (which is assumed to require active suppression of L1) but *not* when switching from L2 to L1 (i.e., when switching to the participant's habitual behavioural response). We conclude therefore that the frontal N2 may reflect the inhibition of habitual behavioural responses.

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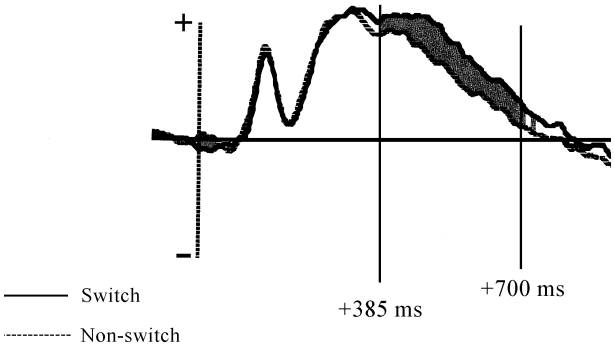


Figure 8. The time course of the ERP for switch and non-switch conditions (collapsed across languages) at parietal sensors P3, Pz and P4. The broken vertical line represents a change of 5 μV ranging from −2.5 μV to 2.5 μV. The solid horizontal line represents a time line of 1000 ms from −100 ms to +900 ms with stimulus onset occurring at 0 ms. Blocks of grey represent time points with statistically significant differences (t-values) between conditions. Note that there is a statistically significant increase in the ERP for switch trials compared to non-switch trials which begins approximately 340 ms after stimulus onset (depicted by the first grey line) and is sustained until around 700 ms after stimulus onset (later grey line).

Differences in the ERP over parietal sensors

While the functional brain-imaging studies reported by Konishi and colleagues (Konishi et al., 1998, 1999) implicate regions of the frontal cortex in response suppression and response switching, other brain-imaging studies have identified more posterior areas of cortex as being involved in language switching. Thus, Price, Green and von Studnitz (1999) reported a PET study in which they investigated the neural mechanisms involved in switching back and forth between languages (German and English) during a language translation task. They found that switching between languages was specifically associated with increased activation of Broca's area in the left hemisphere, and increased activity, bilaterally, within the supramarginal gyri of the parietal cortex; areas that the authors associated with phonological recoding. This finding is consistent with theoretical accounts of language switching proposing that selective lexical access is based upon the active inhibition of the non-target language arising due to the operation of inhibitory connections linking the L1 and L2 lexicons (Green, 1986, 1998a, b), and neuropsychological case reports demonstrating that bilingual patients may become locked into speaking in a single language – despite normal comprehension in *both* languages – after parietal lobe damage (Fabbro, 1999). With this in mind we examined the ERP over parietal cortex for evidence of switch-related effects.

Analyses of the ERP showed a sustained increase in the magnitude of the late positive complex (LPC) for switch trials compared to non-switch trials measured at parietal sensors (P3, Pz, P4). This effect is shown in Figure 8. This sustained difference between switch and non-switch trials began at 385 ms after stimulus onset, and remained significantly different until 700 ms after stimulus onset. Further analyses revealed that this effect was not substantially different for L1 and L2. Both L1 and L2 showed sustained increases in the magnitude of the LPC for switch trials compared to non-switch trials between +385 and +700 ms. We note that this effect is consistent with previous studies demonstrating a sustained increase in the LPC in circumstances requiring executive control of response selection, i.e., during Stroop interference. Liotti, Woldorf, Perez and Mayberg (2000) studied the ERPs associated with colour word naming in a Stroop interference task. They found a sustained increase in the positivity of the LPC for the incongruent compared to the congruent colour-word naming condition. This increase in the positivity of the LPC was found to differ statistically for a sustained period between 500 ms and 800 ms after stimulus onset.

Discussion

In order to switch rapidly and efficiently between alternative forms of response, it may often be necessary to actively suppress other, more habitual, responses as well as select the appropriate behavioural response. In the current study we required participants to switch back and forth between their first and second languages based upon the presence of an arbitrary context (colour) cue. So as to avoid errors on this task, it is likely that participants will need to temporarily suppress access to whichever lexicon (L1 or L2) is not currently required, and, on switch trials, to alter the stimulus–response linkages needed to regain access to the previously suppressed lexicon (Green, 1998a). Furthermore, in the current study the pattern of language switching trials was entirely predictable and made explicit to all participants. Despite the predictable nature of this task, RTs were significantly slowed on switch trials compared to non-switch trials. These results confirm the theoretical distinction between "Endogenous" and "Exogenous" control operations proposed by Rogers and Monsell (1995), who suggested that while some aspects of control can be implemented in advance of the onset of a stimulus, others require that the stimulus be presented before the S–R reconfiguration

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process can be completed. Furthermore, we found that while RTs for L1 and L2 were significantly different for non-switch trials, they did not differ for switch trials. This effect differs from the cross-over interaction effect previously reported by Meuter and Allport (1999). We suggest that these findings do not support the concept of asymmetric switch "costs" in which participants are slower to switch from L2 to L1 than from L1 to L2. Instead, our data are better described in terms of asymmetric "non-switch benefits" in which participants are equally slow when switching from one language to another, but experience an RT advantage for remaining within a language (i.e., during non-switch trials) which is greater when responding in their first language.

It was also shown that language switching was associated with a significant increase in the negativity of the frontal N2 component of the ERP (N320). This result was predicted by recent brain-imaging studies which suggest that response suppression and response switching share a common neural substrate. An important finding from the current study was, therefore, the demonstration that this effect was asymmetric across L1 and L2. Thus, we demonstrated that the increase in the negativity of the frontal N2 component was largest when switching from L1 into L2 but was not statistically significant when switching from L2 into L1. This result is entirely consistent with the suggestion that access to L2 requires active suppression of L1, and with theoretical accounts suggesting that the frontal N2 component is associated with response suppression (Jackson et al., 1999; Konishi et al., 1999; Sasaki et al., 1989).

An important question raised by these results is why the asymmetry across languages (L1 and L2) is different for the RT and ERP data. That is, the RT data show an asymmetry across languages such that the "costs" of switching languages (i.e., switch RT–non-switch RT) is greater for L1 trials than for L2 trials. In contrast, the ERP data show a different asymmetry across languages in that the difference in magnitude of the frontal N2 deflection in the ERP for switch compared to non-switch trials, is *greater* for L2 than for L1. We suggest that these effects are not as inconsistent as they might at first appear. We interpret the RT data as support for the notion that, when switching between languages, there is a requirement to reconfigure the S–R linkages between visual stimuli and phonological outputs. As noted above, there is now good empirical evidence to suggest that this reconfiguration process cannot be carried out in advance of stimulus onset. We note that our own data suggest that participants are equally slow in executing a response on switch trials and that a key aspect of this S-R reconfiguration may be the active suppression of the previously active lexicon (see below for further discussion of this issue). It is likely that the suppression of L1 will require more in the way of active inhibition, and will therefore lead to the observed RT asymmetry across languages. Similarly, we suggest that the asymmetry observed in the magnitude of the frontal N2 on L2 trials *also* reflects the active suppression of the more habitual response (i.e., L1) prior to switching into L2. In our view, this apparent discrepancy between the RT and ERP results stems from the fact that the frontal N2 reflects processes that are in operation to *bring about switching* whereas the RT data reflect the net result of having switched.

In addition to the frontal N2 result, analyses of the ERP also revealed a late and sustained increase in the positivity of the LPC for switch trials at sensors over the posterior parietal cortex (P3, Pz, P4) occurring between 385 ms and 700 ms after stimulus onset. These results are consistent with a recent functional brain-imaging (PET) study of language switching in bilingual speakers, in which activity associated with switching between languages was localised bilaterally to the supramarginal gyri (BA 40) (Price et al., 1999). It should be noted, however, that our current analyses do not allow us to locate the neural source(s) for the increase in the positivity in the LPC associated with switch trials. Such analyses must await the results of an fMRI study that we are undertaking to investigate this issue. We note, however, that this result is consistent with a recent ERP study of response selection in a Stroop colour-naming task (Liotti et al., 2000). In that study Liotti and colleagues found a sustained increase in the magnitude of the LPC between 500 ms and 800 ms for incongruent colour-naming trials compared to congruent colour-naming trials which the authors interpreted as evidence for additional analysis of word meaning. We speculate that our finding of an increased positivity in the LPC over the parietal scalp region associated with switch trials may reflect the reconfiguration of the S–R linkages required to regain access to the previously suppressed lexicon (Green, 1998a), and may be considered analogous to the mechanism of "contention scheduling". In our view these effects may therefore reflect a different form of inhibitory control to that associated with the frontal N2 component, specifically, the operation of inhibitory connections linking L1 and L2 required to bring about access to the previously suppressed lexicon.

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