The temporal dynamics of switching tasks

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I certify that all material in this thesis which is not my own work has been identified and that no material has previously been submitted and approved for the award of a degree by this or any other University.

Signature:………………………………………………….

Abstract

The topic of this thesis is cognitive control: how the brain organises itself to perform the many tasks it is capable of and how it switches flexibly among them. Task-switching experiments reveal a substantial cost in reaction time and accuracy after a switch in tasks. This "switch cost" is reduced by preparation (suggesting anticipatory task-set reconfiguration), but not eliminated. The thesis focuses on the sources of the "residual" cost. Most accounts attribute it to response selection being prolonged on a task-switch trial by task conflict, e.g. by 'task-set inertia' — persisting activation/inhibition of the previous task's S-R rules — or their associative reactivation by the stimulus.

Four experiments used event-related potentials (ERPs) to determine which stages of task processing are influenced by a change in tasks, looking for delays in process-specific markers in the ERP. Experiments 1 and 2 showed that a prepared switch to a reading task from a perceptual judgement delayed early ERP markers of lexical access by a large fraction of the RT switch cost, suggesting that a substantial part of the residual cost arises in processes earlier than response selection, possibly due to task-related attentional inertia. Markers of lexical access observed in the non-lexical task were larger on switch than repeat trials, providing the first electrophysiological evidence of task-set inertia. Experiment 3 examined the effects of an unprepared switch in the same way. ERP waveforms were modulated by a switch before markers of lexical access were evident, suggesting additional processing demands compete for resources with lexical access. A simple delay, however, was not found; post-stimulus task-set reconfiguration does not just insert an extra processing stage. Experiment 4 looked for a delay in the onset of an early ERP marker of emotional processing when the task switched between categorising facial expression and classifying a superimposed letter. No such delay was found in this case, and ERP markers of emotion processing were present to the same extent in the letter task. This suggests that, given appropriate spatial attention, processing facial emotion unfolds automatically, independent of attention allocation to the facial features.

Experiments 5-7 further explored the link between conflict due to processing the irrelevant stimulus dimension and the ERP post-stimulus negativity that accompanies the residual cost. The negativity could be elicited even on trials of non-switching blocks by prior training on classifying the irrelevant attribute of the stimulus using the same responses. But this effect did not seem to result from the trained class of irrelevant attribute attracting more attention.

Finally, Experiment 8 followed up an incidental observation in Experiment 1 to establish the novel observation that a task-switching context abolishes the usual ERP correlate of withholding a response in a go/no-go paradigm, suggesting an interesting interaction between task-set control and response inhibition.

Acknowledgements

To embark on a journey some essentials are necessary, for example, a car and fuel, directions and someone who does the driving. Difficult to say what is more important.

If I regard my PhD as a journey, then the ESRC provided me with all essential material things. Without their funding this research would not have been possible.

My supervisors, Prof. Stephen Monsell and Dr. Aureliu Lavric gave me directions, made sure I stayed on track. So often during the last 4 years I thought how lucky I was to have them on my side. Their interest in, and dedication to, science has always inspired me. I have learned an enormous amount from them and wish there is a chance for this to continue.

But, the driver would also not have reached the destination without the people who cheered her up when she was frustrated, tired or ill. She knew someone would take over the steering wheel for a bit if necessary. These include my dear daughter Elisa, my friends and (previous and current) house mates Felice, Henrietta and Charlotte – it means so much to come home to someone who cares about you. There is Niklas with whom I can share all things German. And there are Tobias and Hannah, Caz and Rosie, Beth and Dale; a unique mixture of PhD students from the cognitive, clinical, animal behaviour and social research groups of our department. I am very happy to be part of such a lovely group.

Being a "mature" student I sometimes wished I had studied earlier, but really, I would not trade in these last four years for anything, thanks to all the people mentioned above.

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Declaration

The research reported in this thesis was carried out at the University of Exeter between October 2007 and July 2011, and was supervised by Prof. Stephen Monsell and Dr. Aureliu Lavric.

This dissertation has not been submitted, in whole or in part, for any other degree, diploma or qualification at any university. Chapters 2 and 5 are articles that will be submitted to scientific journals. Chapter 2 will be submitted to Journal of Experimental Psychology: General, by Elchlepp H., Lavric, A. and Monsell, S.. I conducted the experiments and analyses, wrote the first draft and prepared the figures and tables. My coauthors have edited the manuscript. Further, Chapter 5 will be submitted by Elchlepp, H., Lavric A., and Rumball, F.. Experiment 5 in Chapter 5 was part of a third-year undergraduate project in 2009 and the student Freya Rumball created the stimuli and helped me acquiring the EEG data. Experiment 7 in Chapter 5 was also part of an undergraduate project. The students Kathryn Bennett and Sarah Harvey created the stimuli and acquired the behavioural data. All experiments in Chapter 5 were designed by me under the supervision of Aureliu Lavric. I carried out all analyses, wrote the first draft and prepared the figures and tables. Dr. Lavric has edited the manuscript.

Heike Elchlepp
Exeter, July 2011.

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Introduction

Human behaviour is the result of a complex interplay of external, environmental factors with internal goals, wishes, and intentions. The extent to which behaviour follows our intentions rather than external triggers depends on the adequate functioning of our cognitive system, in particular cognitive control. The last quarter-century has seen a development of theories on cognitive control, from rather simple ideas of an executive controller or supervisory system – usually assumed to be in prefrontal cortex – to an increasingly differentiated set of issues to do with different aspects of control, and increasing progress in identifying control networks in the brain. The most influential of these theories developed by Norman and Shallice (1980, 1986) expanded by Shallice (1988) had its roots in the observation of action errors in daily life and utilisation behaviour of frontal lobe patients. Both phenomena have in common that a stimulus in the environment seems to take control over behaviour against current intentions. This led Norman and Shallice to propose two distinct processes in their action model of control: automatic and willed. Automatic control as the simplest form of action control is supposed to be operated by a mechanism called "contention scheduling", which selects a number of restricted schemas to take control. In that way routine behaviour can be guided. When a novel behaviour needs to be learned or when several schemas compete for selection willed control comes into play. It uses the supervisory attentional system, a controller limited by attentional resources that can organise and monitor schemas in order to achieve correct performance on new and complex tasks. Acknowledging the role of relatively automatic routines that can be triggered by external stimuli and way they are modulated by "higher" control processes was an important step in our understanding of control mechanisms.

One important aspect of control is how the brain organises itself to perform one of the many tasks of which it is capable. To investigate this, substantial effort has been undertaken to probe the mechanisms involved in switching between tasks. To experimentally examine the processes involved in such shifts, a number of task-switching

paradigms have been developed (see Monsell, 2003; Kiesel, Steinhauser, Wendt, Falkenstein, Jost, Phillip & Koch, 2010; Vandierendonck, Liefooghe & Verbruggen, 2010 for reviews). The basic structure is that the participant is presented with a stimulus on each trial to which he/she must respond (usually with a key press on a computer keyboard) following a certain rule or set of rules which defines the task. On some trials this rule changes and on others it remains the same. Paradigms vary in how participants are informed about which rule to apply on a given trial. One of the first switching paradigms had a predictable task sequence. That is participants were told they would always perform a certain number of trials (2, 3, etc.) of each task before switching to the other task (e.g., AABBAABB). This is known as the "alternating-runs" paradigm (Rogers & Monsell, 1995). An alternative version is known as the task-cueing paradigm (Sudevan & Taylor, 1987; Biederman, 1972; Shaffer, 1965) and is described in more detail below; here tasks switch unpredictably and a task cue is presented before or with the stimulus which signals the task to perform on that trial. These two paradigms are the most widely used and most of the previous studies whose evidence will be discussed in this thesis employed one of them. For completeness two other paradigms should be mentioned. In one of them, referred to by Monsell (2003) as 'intermittent instruction' paradigm, participants are told to continue performing one task until a signal (cue) tells them to switch (Gopher, 1996; Gopher, Armony & Greenshpan, 2000). Another relatively recent version of switching paradigm has participants perform a task as long as they wish with the instruction to switch on a certain proportion of trials, leaving the choice when to switch up to them (voluntary switching paradigm (e.g., Arrington & Logan, 2004, 2005; Arrington, Logan, & Schneider, 2007).

A common finding across experiments using all these paradigms is the substantial decrement in performance (longer reaction times and higher error rates) when the task changes compared to when it stays the same; the 'switch cost' (e.g., Allport, Styles, & Hsieh, 1994; Fagot, 1994; Rogers & Monsell, 1995; Mayr & Keele, 2000). Since this phenomenon was first observed, several theoretical accounts have attempted to explain it. At the basis of most of these accounts is the notion that in order to successfully perform a task, the mind must be organised in a certain way: a 'task-set' needs to be in place. Establishing a task-set includes (but may not be limited to): prioritising the task goal, orienting attention to relevant stimulus features, preparing possible motor responses and

enabling the appropriate S-R mapping rules. With practice this task-set may become retrievable as a 'package' (Monsell, 2003).

When we switch to a different task, another task-set has to replace the previous one (or another task-set has to become more active than the present one). In other words, the task-set needs to be reconfigured and this exchange, or the difficulty of accomplishing it, is argued to cause the switch cost. It is an intuitive idea that, if we have voluntary control over task-set implementation/reconfiguration, then giving us the chance to exert this control in advance should diminish the cost of a switch. And this is indeed what the data tend to suggest (e.g., Rogers & Monsell, 1995; Meiran, 1996): longer intervals with foreknowledge of a task change reduce switch costs compared to no foreknowledge or little time to prepare. In the alternating-runs paradigm participants have knowledge of when the task changes because the task sequence is predictable. Rogers & Monsell (1995, Experiment 3) showed that increasing the interval between the previous response and the next stimulus (RSI) results in a reduction in switch cost (which I shall call the *RISC effect*). However, the alternating runs paradigm confounds time available for active preparation with time available for passive decay of the previous task-set (Meiran, 1996). Manipulating the interval available for preparation independently from the time that has passed since the previous response is possible with the task-cueing paradigm. Here too, lengthening the time between presentation of a task cue and the stimulus (the cue-stimulus interval or CSI) results in a reduction in switch cost (e.g., Meiran, 1996). Although these reductions in switch cost can be substantial (often 50% or more) they typically reach an asymptote at CSIs of 0.8-1.5s; this asymptotic cost is often referred to as the "residual" cost (Rogers & Monsell, 1995). This suggests two components to the switch cost: one that can be reduced by employing active, voluntary control (as seen in the reduction in switch cost with preparation) and one that cannot (as seen in the residual switch cost).

Most theorists assume that the active control process in preparation of a task change involves reconfiguring the task-set (but see Logan & Bundesen, 2003; Schneider & Logan, 2005 as discussed below). This might include re-allocating attention to relevant task features (Meiran, 2000) and/or activating the appropriate set of S-R rules and/or suppressing the previously active set (e.g., Mayr & Kliegl, 2000; Lien, Ruthruff, Remington & Johnston, 2005). If this is done before the stimulus arrives, average RT can

be reduced because it avoids an overlap of TSR with stimulus processing. Further, competition due to continuing activation of the irrelevant task-set might be reduced if the new task-set is more strongly established. Logically, task-set *re*congfuration is necessary only on trials when the task changes, but participants may also reinforce the existing task-set during the preparation period on repeat trials. Particularly when switching is unpredictable it seems a useful strategy not to suppress the irrelevant task-set completely since it should be kept available when the task changes again. Evidence that the other task-set is not disabled completely on repeat trials is the presence of a mixing cost that is longer RTs on task-repeat trials in a mixed-task block than in a pure-task block (Jersild, 1927; Allport et al., 1994).

As already noted, the task-cueing paradigm has the advantage that one can independently manipulate the time available for preparation and the time that has passed since the previous response, and hence disentangle the reduction in switch cost achieved by voluntary TSR from any reduction resulting from dissipation of task-set activation from the previous trial. However, the cueing paradigm has one potential confound. When only one cue is used per task, cue changes are always associated with task changes and cue repetitions with task repetitions. This can lead to an inflation in switch cost since cue encoding demands may be greater when the cue changes than when it repeats (e.g., Logan & Bundesen, 2003; Mayr & Kliegl, 2003). Some (Logan & Bundesen, 2003) have even argued that there are no task switch costs on top of cue switch costs. They proposed that participants encode the cue and then the stimulus to form a cue-stimulus compound, which serves to retrieve the correct response from long term memory. When the task repeats (as opposed to switches) cue encoding proceeds faster because of priming from the previous trials. A simple way to disentangle task switch costs and cue switch costs is to use two cues per task. Here, the cue changes on every trial and cue repeats are avoided altogether. Doing so, several authors (Mayr & Kliegl, 2003; Monsell & Mizon, 2006; Schneider & Logan, 2007) found task switch costs over and above cue switch costs. The extent to which task switch costs can be reduced by the opportunity to prepare (controlling for the cue repetition confound) also seems to depend on participants' expectation of a switch in tasks. Monsell and Mizon (2006) found that a higher switch probability (50% versus 25%) reduced overall switch costs and the RISC effect, and argued that this was likely to be because when the expectation of a task switch was high participants tended to start preparing for the switch

already before the cue was presented (i.e., also on trials that could turn out to be task repeats). A low switch probability (e.g., 33%) reduces/eliminates this tendency and allows a cleaner assessment of preparation that is switch-specific. This highlights two important issues when using the cueing paradigm: "true" task switch costs can only be measured when two cues per task are used, and to ensure preparation is switch-specific the probability of a switch in tasks needs to be low.

Long preparation intervals leaving time for reconfiguration improve switching performance, typically reducing the switch cost by 50% or more. Yet, performance never seems to reach the same efficiency as on repeat trials, as the existence of a residual cost shows (though there have been claims that the switch cost can be eliminated by the right kind of cue and short trial blocks (de Jong, 2000) and presenting the cue only briefly in a long CSI (Verbruggen, Liefooghe, Vandierendonck, & Demanet, 2007) - but see also Nieuwenhuis and Monsell (2002). The underlying causes of this residual cost have been subject to debate in the literature and several theories have been developed to explain this phenomenon. The following section will discuss these theories in more detail.

Theories of the residual switch cost

Common to most theories which try to explain this phenomenon is the notion of task-set conflict, which is thought to manifest itself at two levels, the task-set level and the response level. In most task-switching experiments two or more sets of S-R rules are defined linking stimulus categories, or individual stimuli, to responses. A particular stimulus can be mapped to the same response in both tasks (*congruent* stimulus) or different responses (*incongruent* stimulus). If a stimulus has a response mapping in only one of the tasks it is said to be *univalent*. Performance differences between these types of stimuli can inform us about the different levels of conflict. Conflict at the level of S-R mappings is expressed in slower responses, more errors and often a larger switch cost on incongruent compared to congruent trials (e.g., Sudevan & Taylor, 1987; Rogers & Monsell, 1995; Goschke, 2000). Whilst on congruent trials crosstalk from the irrelevant S-R rule should help activate the correct response, on incongruent trials it will activate the wrong response and this response conflict needs to be resolved by longer sampling or possibly active suppression of the irrelevant response or S-R mapping. However, it is also often found that, despite facilitation from any crosstalk at the level of response activation, performance on congruent trials is

worse than on univalent trials (e.g., Rogers & Monsell, 1995; Aron, Monsell, Sahakian & Robbins, 2004; Rubin & Koch, 2006; Steinhauser & Hübner, 2007), which demonstrates conflict between whole task-sets. Such task-level conflict could arise at the level of attentional selection of the relevant stimulus dimension, or in other hypothetical components of the task-set such as mutual inhibition between goal representations (as in the mutual inhibition between task nodes in connectionist models of the Stroop effect (Cohen, Dunbar & McClelland, 1990) and task-switching (Gilbert & Shallice, 2002).

This review will start with accounts of the residual cost that view task-set conflict and interference as the main origins of the residual cost of a task-switch. The earliest account, proposed by Allport et al. (1994), invoked the construct of *task-set inertia*. These authors argued that the task-set of the previous trial lingers on and affects performance on a switch trial in two ways: activation from the previously relevant task conflicts with the currently relevant one, and inhibition of the previously irrelevant task has to be overcome because it is now relevant. Allport et al. initially suggested that switch costs were entirely caused by passive carry-over effects from the previous trial rather than active control processes. But when it was found that the (mean) switch cost seemed to have two components, one that can be reduced with active preparation and one that cannot (Meiran, 1996; Rogers & Monsell, 1995) the idea of "inertia" seemed more appropriate to account for the apparently passive component — the residual cost.

Support for the importance of task-set inertia comes from the observation of asymmetrical switch costs. That is, when switching between two tasks of unequal strength it is harder to switch to the dominant compared to the weaker task (Allport et al., 1994). If switch costs arose from an active reconfiguration process, this should be easier for the easier task (if there was any difference) hence the switch cost should be smaller. But Allport et al. found exactly the opposite. They attributed this to the difficulty of overcoming the substantial inhibition that had to be applied to the stronger task to enable performance of the weaker task (see also Meuter & Allport, 1999). Yeung & Monsell (2003) replicated the paradoxical asymmetry of switch costs but also found conditions under which the asymmetry reversed. They suggested maximal interference between tasks is necessary for the paradoxical pattern to arise. Such conditions exist, for example, when there is an overlap of relevant and irrelevant stimulus features (when they are simultaneously

presented) and/or response sets. Moreover, they proposed a dynamic model of cognitive control which explains switch cost asymmetry as arising from an interaction between persistent activation of the task-set, and top-down activation of the required task-set dynamically adjusted to achieve an acceptable error rate. More precisely, they argue that more top-down input is required when task interference is high that is, when switching to the weaker task. For repetitions on the other hand this interference is greatly reduced resulting in less control being applied, which in turn reduces the repetition benefit for the weaker compared to the harder task.

More suggestive of an inhibitory component of task-set inertia is the phenomenon originally labelled "backward inhibition" (Mayr & Keele, 2000) but also referred to as the "N-2 repetition cost". It describes the finding that RT is longer on the final trial of an ABA task sequence than of a CBA sequence —see Koch, Gade, Schuch and Philipp (2010) for review. The inertia account is that the inhibition applied to suppress task A in favour of task B on the second trial of the ABA sequence persists, causing extra difficulty when A is required again on the third trial. However, in the original version of the paradigm all trials were switch trials and it is hence difficult to obtain a task-switch cost, and to determine to what extent the N-2 repetition cost contributes to it. Moreover, it is not clear whether inhibition is applied to the same extent when there is a non-trivial chance of a task repetition. Phillip and Koch (2006), for example, observed that when repeat trials were included into the paradigm the N-2 repetition cost was almost eliminated, questioning its contribution to the kind of task-switch cost measured in most switching paradigms.

Another inhibitory variant of the task-set inertia hypothesis could be referred to as *response-contingent reconfiguration.* This account combined the idea of task-set inertia with the assumptions that effective inhibition can be applied only post-stimulus (not during preparation), and is applied specifically during response selection, not before. While preparation reduces switch cost, the residual cost implies that task-set reconfiguration is incomplete until the new task has been performed at least once. Schuch and Koch (2003) presented a "no-go" signal along with the target stimulus, telling the subject to withhold a response. This eliminated the switch cost on the following trial. They argued that "when switching from one task to another in typical task-switching paradigms, a conflict arises between the previous and the current category–response rules, and it becomes necessary to

inhibit the previous set of rules", (p.101). That is, even after maximal pre-stimulus preparation, conflict arises after the stimulus, and a task-set suppression process must be applied to resolve it and ensure that the appropriate response is produced. Until that suppression has been applied, task-set reconfiguration is not complete and does not "stick". According to Koch and colleagues, this suppression process is also the source of the n-2 repetition effect. Verbruggen, Liefooghe and Vandierendonck (2006) went on to show that response selection rather than response execution seems to be the critical operation that has to be accomplished to get switch costs on the next trial. In their experiments participants had to select the response on each trial but executed it only on some trials but not on others. Having selected a response led to switch costs on the subsequent trial which could be taken as evidence that this stage in task processing is crucial for the full implementation of task-set. It has to be noted, though that switch costs were found to be larger when the response was not only selected but also executed, which might suggest some contribution of response execution to the switch cost (Philipp, Jolicoeur, Falkenstein, & Koch, 2007).

There is another version of the response-contingent reconfiguration account that does not appeal to inhibition in this way. Meiran et al. (2000, Meiran, Kessler, & Adi-Japha, 2008) propose that task-set reconfiguration happens at two levels: reweighting perceptual attention parameters, and reweighting the associations between responses and their meanings. They have argued that while attention can be redirected to a different dimension during the preparation interval, it is only when the participant actually responds that response-set biasing (changing the meaning of the response set) is accomplished – hence the residual cost.

Comparing the different accounts demonstrates that the contribution of inhibitory processes in task switching is quite a widespread assumption. There is, however, also contradictory evidence. For example, Lien, Ruthruff and Kuhns (2006) investigated the role of inhibition in task-switching using bivalent stimuli (containing the dimensions of both tasks) and univalent stimuli (containing only one task dimension). Their rationale was that if inhibition is carried over from the previous into the current trial, performance on the current trial should depend on whether the previous stimulus was bivalent or univalent. In particular, if responding to a bivalent stimulus includes inhibition of the irrelevant dimension, switching to that dimension should be hard and performance worse because

inhibition needs to be overcome. If the stimulus is univalent, one has not encountered the currently relevant dimension on the previous trial so performance should be better. This was tested in an alternating-runs paradigm (AABB) and an all-trials-switching procedure (ABAB, which unconfounded current valence from previous valence). Interestingly, when switching required responding to the previously irrelevant task dimension, performance was not worse than when switching from a stimulus that did not contain this dimension, which questions the contribution of task-set inhibition to switch cost. Lien et al. argued that task-set activation and competition are responsible for the switch cost. They speculate that inhibition might occur but is either not adaptive or is resolved by top-down control applied in the preparation interval.

Associative reactivation of a competing task-set. The task-set inertia account was reinterpreted by Waszak, Hommel and Allport (2003). Instead of explaining switch costs with a passive carry-over of task-set activation/inhibition from the previous trial, they now argued that interference arises from the stimulus reactivating a task-set with which it was previously associated. By means of manipulating the associative history of particular stimuli they found larger switch costs when stimuli were previously encountered in the context of both tasks compared to when they had previously been encountered only in the same task. This effect was found even if the time of the previous encounter was many trials (more than 100) before. This theory is attractive because it provides a rationale for why there are long-term effects (they arise from associative learning, not persistence of activation) and why advance preparation is only partially effective: as in the Schuch and Koch account, one cannot suppress the source of conflict until conflict happens, and it is only after the stimulus has reactivated the competing task-set that conflict happens. However, for this theory to provide an account of the residual switch cost, these stimulus-triggered priming effects have to be larger for switch than repeat trials. Whilst strong effects of prior associations with a competing task are reliably found on response latencies, recent investigations by Monsell and Mizon (under revision) show that the effect is often not modulated by switching. While the associative history theory was originally proposed as an alternative to task-set inertia, Waszak et al. (2005) acknowledged that task-set inertia (transient persistence of task-set) is also required to explain why switch trials are particularly vulnerable to the effects of task-set reactivation. In their 2005 article the associative history theory was combined with the inertia account by making a distinction

between two processes: between-task negative priming — that is, slower responses if the currently relevant response to that stimulus was suppressed in the previous task, and long-term competitor priming that is facilitation of the currently competing response because it was employed in the previous, competing task. Negative priming was only observed when the stimulus set was small, not when it was large.

Other attempts to explain the residual switch cost have regarded control processes as possible sources; some argue control is accomplished as a result of selecting a response (e.g., Meiran et al., 2008; Schuch & Koch, 2003, as described above). Others proposed that the residual cost results from control processes that can only be employed once the stimulus is presented or that failed to be accomplished during the CSI.

Exogenously triggered completion of reconfiguration. Having argued that the part of switch cost that can be reduced with preparation involves an active process of task-set reconfiguration, Rogers & Monsell (1995) attributed the residual switch cost to the completion of this process, which can only be done on arrival of the stimulus. The fact that stimuli can trigger actions that were not intended (as seen in frontal lobe patients with utilisation behaviour and capture errors in healthy adults) emphasized a link between stimulus attributes and task-sets. Further, their experiments showed that performance was worse when the stimulus contained an irrelevant attribute that was previously associated with another task. Hence, they "…propose that the same association between stimulus attributes and task-set that results in a tendency to perform a task when we do not intend to perform it is also effective in completing the process of reconfiguring for that task when we do want to perform it." Rubinstein, Meyer and Evans (2001) elaborated on this idea, suggesting that what can be achieved in the preparation interval is loading the current task goal into working memory, but then the stimulus needs to be present for the second stage of "rule activation" such that once the goal is activated and the stimulus is identified the rule can be applied to it. For example, if the goal is to identify a stimulus as vowel or consonant and the stimulus is identified as a vowel (or containing a vowel), subsequently the S-R rule for vowels is retrieved/ activated. Whilst one can rehearse the S-R rules for both vowels and consonants in the preparation interval, the specific rule for vowels can only be given priority (i.e., additional activation) once the stimulus is presented. Hübner, Kluwe, Luna-Rodriguez and Peters (2004) challenged the idea of an exogenous component of TSR

arguing that the switch cost in Rubinstein et al.'s study was not residual (only one, short, 150ms- RSI was used) and immediate stimulus repetitions contributed to an inflation of switch costs. To deal with these shortcomings, their own experiments manipulated the complexity and familiarity of S-R rules to produce reconfiguration demands that differed in how time consuming they were, hence tapping into the rule activation stage. Their results indicated that more complex and less familiar rules did not increase switch costs which made them doubt the existence of an exogenous stage of TSR.

Probabilistic failure to engage the task-set. De Jong (2000) explained both the reduction in switch cost with preparation and the residual cost by arguing that TSR is an all-or-none process. He assumed that on a proportion of trials preparation succeeds — in which case performance is as good as on a task-repeat trial, and on some trial it fails — in which case there is no improvement in performance at all relative to a no-preparation trial; the residual switch cost arises from the average of these two outcomes weighted by their probability. The main evidence favouring this account is that (in the alternating runs paradigm, where task-repeat trials show no effect of preparation) RT distributions on prepared switch trials could be modelled as a mixture of RTs from unprepared switch and prepared repeat trials (De Jong, 2000; Nieuwenhuis & Monsell, 2002). It remains, however, puzzling that even strong incentives for preparation and ample time allowing multiple attempts to engage in TSR still leave a reliable residual cost. Lien et al., (2005) found full preparation for some S-R pairings of a task and virtually none for other pairings suggesting "people do not prepare all of the task some of the time, they prepare some of the task all of the time" (p.299 but see Monsell & Mizon, 2006 for critique). Moreover, recent neuro-physiological evidence questions the all-or-none nature of preparation, as will be described in more detail in the ERP section below.

A feature of most of accounts of the residual cost is that they assume that the residual cost of a task-switch arises at the response-selection stage of processing, not earlier stages (e.g., response contingent reconfiguration- and inhibition-related versions of the inertia account). The original inertia account and its associative retrieval version do not logically require that the locus of the residual cost is response-selection, but often this assumption has been made (e.g., Allport et al., 1994 explaining the effect of task-set inertia as "the additional time for the system to settle to a unique response decision (or response

retrieval) after the next imperative stimulus has arrived", p.437). The TSR accounts make no claims about a particular locus. However, if rule activation is an additional component to TSR this would need to be largely completed before response selection begins, so that the S-R rules appropriate to the current task are more active than the alternative set(s). To inform theories on the causes of the residual cost it would hence be useful to establish exactly which processes are prolonged after a prepared switch to another task. Reaction times can only give us the end result of the decision process, and inferences about the locus of effect of particular factors are necessarily indirect (e.g. Sternberg's, 1969, 1998, additive factors method). One technique that is can in principle more directly localise effects such as the residual cost within the sequence of processes underlying reaction time is the use of event-related potentials (ERPs). Three experiments reported in this thesis in Chapters 2 and 4 attempted to determine the locus (or loci) of the residual switch cost in the latent interval using ERPs. However, while locating switch induced delays with respect to response selection and other processes may rule out certain variants of the theories considered above, it is not sufficient to distinguish between TSR-based and conflict-based accounts of the residual cost. Three further experiments (Chapter 5) attempt to investigate this issue.

ERP studies of task-switching

Behavioural studies have provided valuable insights about how we switch between tasks, but they are limited when it comes to measuring the temporal evolution of processing both in preparation for and following the stimulus. This is probably the reason why the last decade has seen a substantial increase in publications of ERP studies on task switching. The majority of these have been interested in how we prepare for a switch in tasks and how this is reflected in the ERP. This is one reason why the series of experiments described in this thesis focus on the less well examined post-stimulus interval. The following paragraphs will review what is known to date about switch-induced ERP modulations and how results of those studies can inform the above described theories starting with the preparation interval.

Pre-stimulus preparation-related ERPs. Several switch induced modulations in long cue-stimulus intervals (CSIs) have been proposed to reflect preparation for a switch. Of those, the most consistently reported is a protracted, centro-parietal positivity for switch compared to repeat trials emerging from about 400-500ms after cue onset, and lasting for several

hundred milliseconds, sometimes overlapping into the stimulus interval. This positivity has been observed in the alternating runs paradigm (e.g., Karayanidis, Coltheart, Michie & Murphy, 2003; Wylie, Javitt, & Foxe, 2003a, 2003b) and the task-cueing paradigm (Minussi, Marzi & Nobre, 2005; Nicholson, Karayanidis, Poboka, Heathcote & Michie, 2005; Nicholson, Karayanidis, Bumak, Poboka & Michie, 2006; Kieffaber & Hetrick, 2005; Rushworth, Passingham & Nobre, 2002, 2005; Astle, Jackson & Swainson, 2006; Lavric, Mizon & Monsell, 2008). Using temporal PCA, Lavric et al. (2008) extracted a component that captured the posterior positivity along with an anterior negativity. Its amplitude correlated positively over participants with a behavioural performance index of the reduction in switch cost. Within participants, fast switch trials associated with a smaller switch cost showed larger amplitudes (relative to fast repeat trials) of the positivity than slow switch trials, suggesting that these ERP modulations reflect successful TSR. This was confirmed by a recent investigation of Karayanidis, Provost, Brown, Paton and Heathcote (2011) who partitioned ERP waveforms according to participants' RT distribution (fastest to slowest 5% of the trials). Amplitudes of the positivity varied as a function of RT interval showing a reliable linear decline with increasing RT on switch trials. For repeat trials a much smaller positivity was found, which did not vary according to RT. Whilst Lavric et al.'s analyses suggested that the late positivity and the anterior negativity reflect the same underlying process (they covaried over subjects, hence PCA allocated them to one component), others have argued that they are distinct. Müller, Swainson and Jackson (2007) and Astle, Jackson and Swainson (2008) found the anterior negativity (but not the posterior positivity) modulated by response valence with larger amplitudes for bivalent versus univalent responses. Further, Astle et al. (2008) observed a frontal negativity when subjects had to respond overtly (with a key press) but not when a covert response (mental count) had to be made. This, along with the fact that the negativity was larger for bivalent versus univalent responses, led them to conclude that it reflects competition for a single motor response.

Studies that used PCA to disentangle components underlying the ERP waveform (Lavric et al., 2008; Elchlepp, Lavric, Mizon & Monsell, 2011) dissociated an earlier P3 from the later switch specific positivity. Jost, Mayr, and Rösler (2008) found no P3 after cues in single task blocks but a P3 was present in mixed blocks for switch and repeat trials. They suggested that P3 reflects the updating of task goals and this is required whenever a

cue is presented, i.e. on both switch and repeat trials. This could be why switch-repeat differences are often not large in this time range.

Several studies also report a very early but brief extra positivity on switch trials starting ~200ms after cue onset (Rushworth et al., 2002, 2005; Astle et al., 2008; Lavric et al., 2008; Elchlepp et al., 2011). The earliness of this component and the fact that its amplitudes were not correlated with behavioural measures of preparation led Lavric et al. conclude that it might reflect an early registration for the need to switch rather than the start of the reconfiguration process. One further, less consistently reported modulation is a longer latency switch negativity. This has been reported in only a few studies with very long CSIs (Tieges, Snel, Kok, Wijnen, Lorist & Ridderinkhof, 2006; Tieges, Snel, Kok, Plat & Ridderinkhof, 2007; Astle et al., 2008) and seems to emerge only after the late positivity has resolved (after ~800ms). Its relationship with the frontal negativity that is concurrent with the positivity is unclear but it seems to reflect a different process since they don't overlap in time and the topography of the later modulation is more broad and central. Tieges et al. (2006, 2007) have proposed it reflects active maintenance of task-set.

Post-stimulus switch-related ERPs. More relevant for the investigations reported in this thesis is, however, what happens after stimulus onset. The most consistently reported switch-repeat difference in long CSI post-stimulus intervals is greater negativity for switch than repeat starting ~300ms after target onset with a centro-parietal distribution (Karayanidis et al., 2003; Nicholson et al., 2005; Lavric et al., 2008; Swainson et al., 2006). This component is particularly interesting for the current investigations because it has been linked with task-set conflict (Lavric, et al., 2008; Nicholson et al., 2005) and the residual switch cost. The conflict-related interpretation of this modulation was initially motivated by the observation of a similar negativity found in the same latency range in studies investigating Stroop interference (N450; West, 2003). Recent ERP task switching studies have supported this link. Particularly informative are studies that have contrasted situations where task-set conflict is large rather than small. Such a comparison is provided by switching between stimuli that afford responses in both tasks (bivalent stimuli) compared to those that afford and have responses in only one task (univalent stimuli). The first study comparing switching in bivalent blocks with univalent blocks (Karayanidis et al., 2003) found a smaller switch cost in the univalent condition and a reduced switch-induced

negativity in the univalent compared to the bivalent condition in electrode Pz. In Poulson, Luu, Davey and Tucker's (2005) study participants switched between bivalent and univalent stimuli within a block. They found a larger negativity for bivalent versus univalent stimuli, although here valence did not interact with switching in the range of this negativity possibly due to an overlap of the preparation related positivity on switch trials from a relatively short (450ms) CSI. Finally, our own between-study univalent-bivalent comparison (Elchlepp et al., 2011) found the amplitude of the post-stimulus negativity reduced in the univalent compared to the bivalent study.

There is some evidence that the post-stimulus negativity may have several underlying causes, which could include conflict at the level of task-set and/or at the level of responses (as distinguished in the previous review). Temporal PCAs on post-stimulus amplitudes, for example, always extract a number of components capturing several switch negativities (sometimes with slightly different topographies, e.g., Lavric et al., 2008; Elchlepp et al., 2011, see also results of the experiments in this thesis). The early part of this negativity has previously been attributed to differences in the N2 component of the ERP (peaking ~300ms). Swainson et al., (2006) observed N2 differences when participants switched between responding immediately and having to postpone their response in a simple categorization task. Gajewski, Kleinsorge and Falkenstein (2010) recently investigated the relationship of switching between task-sets and switching between response modes (go-nogo). Participants responded to digit stimuli judging either their parity or magnitude after the identity of the task was signaled 1000 ms in advance by a cue (square=magnitude, diamond=parity). Digits could be of two colours; green indicated a go response (i.e., key press, 75% of trials), red indicated that the response had to be withheld (nogo, 25% of trials). Nogo trials never appeared in close succession and their frequency was equal on switch and repeat trials. N2 amplitudes were found to be increased on trials where the task, the response mode, or both switched. On trials following a go response, N2 amplitude differences between switch and repeat correlated marginally with the residual switch cost (the larger the amplitude difference the greater was the residual cost). On trials following a go or nogo trial, N2 latency differences correlated reliably with the residual cost with a larger delay in N2 for switch (versus repeat) trials being associated with a greater residual cost. In line with previous conflict accounts of the N2 component (e.g., Nieuwenhuis, Yeung, van den Wildenberg, & Ridderinkhof, 2003), Gajewski et al. (2010)

argued that "the fronto-central N2 reflects a decision process (Ritter, Simson, Vaughan & Friedman 1979; Ritter, Simson, Vaughan & Macht, 1982), e.g., the mapping of a stimulus onto a response category, which is intensified and prolonged when interference between C–R (category-response) associations has to be resolved". Although this could be quite strong support for a link between a post-stimulus negativity and the residual cost one has to be cautious as to how "residual" the cost in this study was. Only one cue per task was used (confounding cue switch cost with task switch cost) and the stimulus had to be additionally interpreted in terms of whether that trial required a response or withholding it, i.e., go and nogo were not determined by the classification outcome (odd/even or smaller/larger than five), but by stimulus colour. In fact, subjects could abandon task processing altogether as soon as they perceived the colour red since no response was required on those trials. This also makes the classification of the subsequent trial as switch or repeat difficult since one cannot be sure whether or to what extent participants had implemented the task-set on a nogo trial.

Although some authors (e.g., Lavric et al., 2008) favour a conflict based explanation of the post-stimulus switch negativity, others have offered an alternative interpretation. For example, Swainson et al., (2006) proposed that this switch-repeat ERP difference reflects active consolidation (as expressed in larger P3b amplitudes) on repeat trials, which is why they refer to it as 'repeat positivity'. They based this on the fact that they found this modulation only when the task sequence was predictable (as in the alternating-runs paradigm). However, if this ERP effect reflected task-set consolidation on repeat trials, it is not clear why behavioural evidence from alternating runs (Monsell, Sumner & Waters, 2003) shows that RT fully recovers from a switch on the first repeat in a run and there is no further benefit suggestive of consolidation. Furthermore, other studies (e.g., Nicholson et al., 2005; Lavric et al., 2008) have found this component also with unpredictable switching so that the extent to which it is modulated by sequence predictability remains an open issue. Jamadar, Michie and Karayanidis (2010) recently argued that the switch negativity is not simply a modulation of the P3b but is superimposed on a number of components such as P2, N2 and what they term posterior late positive component (LPC). Their second experiment investigated performance on switch and repeat trials as a function of whether the preceding trial's task cue was informative (i.e., a cue whose colour predicted the task on that trial) or uninformative (here the stimulus colour specified the task). They found switch

cost and the switch negativity substantially reduced on informative cued trials that were preceded by non-informative cued trials (in contrast to those that were preceded by an informative cue). However these effects were due entirely to modulation of performance and ERP on repeat trials. In particular, waveforms for repeat trials that were preceded by an uninformative cued trial were more negative than those preceded by an informative cued trial, making the former more similar to switch trials. This led them to conclude that the switch-repeat difference causing the negativity is due to priming effects. More precisely, prepared repeat trials benefit from priming effects of the previous trial while unprepared repeat trials do not, making them more similar to switch trials.

In post-stimulus ERPs from unprepared switch trials the switch negativity is often overwritten or delayed by a preceding positivity. In fact, this positivity has a very similar topography to the one found in the late parts of long CSI cue intervals. It is consistent with the idea that this late posterior positivity reflects TSR, and that if TSR is not done before stimulus onset it needs to be done afterwards, that this component is pushed into the post-stimulus interval when CSI is short. Similar to long CSI ERPs it emerges ~500ms after cue onset (i.e. ~300ms after stimulus onset). This shift of the positivity was found in the alternating runs (Karayanidis et al., 2003) as well as the cueing paradigm (Nicholson et al., 2005; Lavric et al., 2008). Lavric et al. (2008) also found a substantial overlap of this positivity into the target interval also on long CSI trials with slow responses reinforcing the notion that if TSR was not done before stimulus onset it needs to be done afterwards.

The idea of investigating how known ERP components are modulated in amplitude and/or latency by a task switch (such as attempted by Gajewski et al. with the N2) is promising since it could potentially address the question of what stages of task processing are affected by a switch. Unfortunately, even the most researched ERP components do not come with a secure functional label. A rare exception is the lateralized readiness potential (LRP), an activation created over the motor cortex in the hemisphere contralateral to the hand to be moved ~150ms before the actual movement. In several experiments Hsieh and colleagues (Hsieh & Yu, 2003; Hsieh & Liu, 2005; Hsieh, 2006) assessed LRP latencies for switch and repeat trials separately and found them to be delayed when the task switched versus repeated. They further investigated how switching affects P3 latencies assuming that P3 reflects the stage of stimulus evaluation. The finding that P3 was not delayed by

switching while LRPs were led them to conclude that switching affects later stages of task processing, namely response selection, as proposed by several models of the residual cost. P3, however, is sensitive to a number of factors (e.g., saliency or frequency of a target) and its magnitude may be modulated by switching per se. Even if one found a delay in P3 one would not be able to specify uniquely which process is delayed. That means Hsieh et al.'s results merely suggest, in line with almost all theorists, that response selection or earlier processes are delayed by switching. To partition the switch cost amongst those earlier processes the experiments described in Chapter 2 took a new approach, which will be described in more detail in the introduction to that chapter.

fMRI studies of task-switching

With the advance of neuroimaging, particularly fMRI, a wealth of studies have tried to find areas in the brain that are consistently activated when we switch between tasks. Some of these have looked at the switching process as a whole, some have tried to find the regions activated during task-set preparation. The large variety of paradigms and tasks used in those studies, an estimated type I error rate between 10-20% (Wager, Lindquist, & Kaplan, 2007) of reported activations, and the complex dynamics of the underlying neurophysiological processes has resulted in a map of regions active during switching that has become less and less conclusive as it covers increasingly larger areas of the brain. This short review will therefore focus on results of a meta-analysis recently conducted in our lab (Stevens, Monsell & Lavric, in preparation) and mention only a few single studies that were seen as particularly relevant. As mentioned earlier an important distinction when characterizing the processes involved in switching is the division into preparation-related and stimulus-related activity. Whilst this can be done easily with ERPs it is a challenge for fMRI studies due to the sluggishness of the hemodynamic response. Changes in blood oxygen level in response to an event take several seconds making it difficult to distinguish cue related from stimulus related activity. Researchers have, however, tried to find ways to overcome this problem such as increasing the CSI to several seconds, presenting informative along with uninformative cues or omitting the stimulus on some trials. In their meta-analysis Stevens, Monsell and Lavric created a database of 27 fMRI studies published after 1999 including data of healthy participants only. Multi-level Kernel Density Analysis (MKDA, originally developed by Wager et al., 2007) was used to determine consistent peak activations across studies, a technique that takes into account that multiple activations reported by the same

study are not independent. Contrasting activations on switch with those on repeat trials revealed two consistently activated areas: the superior medial frontal cortex and the left inferior frontal junction (IFJ). Most studies also showed activations in the parietal cortex but due to the great spatial variability of these activations within this part of the cortex no voxels (apart from one in the left parietal lobule) reached significance in the meta-analysis. Two methods were employed to look at the impact of preparation on switching; first, switch-repeat contrasts were run for studies that did allow at least some time for preparation (CSI longer than 250ms) and for those who did not (CSI smaller than 250ms). These contrasts showed that having time to prepare for a switch was associated with consistent activations in the left IFJ while switching without preparation resulted in consistent activations medial frontal cortex (ACC, preSMA). Interestingly, the second strategy, pooling over studies that looked at cue related activity and reported a switch by preparation interaction, found consistent activations in a different region of the brain, the left superior parietal lobule. Although clarification is still needed as to why the two preparation-related contrasts revealed switch specific activity in different regions of the brain results hint to an involvement of those regions in active task-set reconfiguration. In particular, the left IFJ has been shown to be important for the updating of working memory (Wager & Smith, 2003), or the retrieval of abstract task representations (Bunge, Kahn, Wallis, Miller & Wagner, 2003). It is further located at the junction of three functional neuroanatomical domains, namely the language domain, the premotor domain and the working memory domain and could hence be involved in integrating information from these domains. The verbalisation of task goals has been argued to be important in task preparation (Goschke, 2000; Miyake, Emerson, Padilla & Ahn, 2004) and regions close to the IFJ are thought be involved in phonological processing and silent articulation. Inner speech to facilitate uploading a new task rule into working memory along with their S-R rules (preSMA) are also likely to be part of TSR.

The parietal lobe is argued to be specialised in processing linking visuo-spatial input to motor output. The part in the right hemisphere has been argued to be predominantly associated with the redirection of visual attention while the left hemispheric part is more specialised in biasing motor output (Rushworth, Krams & Passingham, 2001). Stevens, Monsell and Lavric's meta-analysis found consistent activations in both hemispheres when time for preparation was given; in the right hemisphere these did not

differ for switch and repeat trials while the left parietal activations (superior parietal lobule) reflected switch specific preparation. Tunik, Johnson-Frey and Grafton (2005) found that TMS applied to the region around the left intra parietal sulcus disrupted people's ability to adjust a grasping movement after a change in goal, which could suggest that this area is involved in implementing and biasing S-R mappings. This in turn is likely to be an important part of TSR.

When there was no time for preparation, consistent switch-specific activations were found in the pre-SMA, a region that had previously been associated with preparing motor actions (Picard & Strick, 1996), in particular implementing S-R rules at a higher motor level (Brass & van Cramon, 2002). Those activations were also found with time for preparation but here no difference was found between switch and repeat trials. One could speculate that when there is time to prepare people rehearse the already implemented S-R settings on repeat trials so activation differences between switch and repeat are small. When there is no time to prepare people are still able to respond correctly on repeat trials since the S-R settings are already implemented, on switch trials on the other hand S-R settings must be updated, otherwise a wrong response will be given.

In summary, fMRI studies have isolated brain areas that are consistently activated when we switch between tasks. Those include the medial frontal cortex (pre-SMA, ACC) and left IFJ. Some studies have also reported an involvement of right IFG (e.g., Aron et al., 2004) which is assumed to be responsible for the inhibition of inappropriate responses. The extent to which inhibition is involved in switching is a still matter of debate and might vary from paradigm to paradigm (which might also be a reason why this region did not show consistent activations in the meta-analysis described above). In spite of the variability in the brain regions reported in fMRI studies of task-switching, there does seem to be some consistency and systematicity in the relation between the activation of particular regions and aspects of task-set control such as preparation, but it is clear that a complex network is involved.

Whereas the studies discussed in the previous paragraphs were largely interested in isolating regions of the brain that are associated with switching or the preparation for a switch, Yeung, Nystrom, Aronson and Cohen (2006) took a different approach. They

attempted to address a question about a functional mechanism of switch costs using fMRI activations as a measure of task-specific activation. In particular, they used activations of face and word specific brain regions to investigate processes underlying the residual cost focusing on the contribution of task-set inertia. Participants switched unpredictably between mini-blocks of four trials of either a face discrimination or word categorization task. Localizer tasks were used to establish brain regions associated uniquely with each of these tasks. Yeung et al. found that in the switching blocks activation of the face- and word-specific regions predicted the RT cost of switching *away* from that the corresponding task — e.g. greater activation in the face-relevant region correlated with a larger cost of switching to the word task. This provides the first neural correlate of task-set inertia and is suggestive of persisting activation of a whole processing pathway rather than of S-R rules only as assumed by some of the above theories. However, in the same way that it is difficult to isolate activity specific for preparation of a change in tasks with fMRI it is equally hard to measure activity related to "true" residual cost. With a CSI of only 450 ms it is likely that the switch cost in this study was not purely "residual".

Outline of thesis

To summarise, the part of the switch cost that can be reduced with preparation has been attributed to an active process of task-set reconfiguration; the sources of the residual cost are less clear. Most theories about the residual cost assume it is caused by conflict, either from passive carry-over of task activation and/or inhibition from the previous trial or through reactivation of one or more competing task-sets previously associated with the stimulus. These theories appear to assume that what is slowed by this conflict (or by dealing with it) is response selection. One main focus of this thesis was to investigate the temporal locus of the switch cost within the latent interval, which can potentially inform about its causes. The experiments described used event-related potentials because their excellent temporal resolution allows a precise measurement of the timing of task processing stages and their modulation by switching. The basic strategy was to use markers in the ERP waveform of processes prior to response selection, and to ask whether a task switch delayed the onset of such markers and, if so, by what fraction of the amount by which a switch prolonged reaction time.

Experiments 1 and 2 (reported in Chapter 2) investigated whether early ERP markers of lexical processing were delayed immediately after a prepared switch to a lexical task compared to repeated performance of that task. Both experiments provided evidence that a substantial fraction of the RT switch cost can be attributed to the slowing of processing in or prior to the early stages of lexical access, and hence well before response selection. However, the impact of the results on theories about the residual cost relies on the assumption that the participants in these experiments had used the cue-stimulus interval for effective preparation, i.e. that the switch cost measured was truly "residual". To establish this, Experiment 3 (reported in Chapter 3) used the same tasks as in Experiment 1, but a short CSI, to provide appropriate behavioural evidence of preparation. The ERPs of this experiment were also examined with regards to the effect of an unprepared switch on task processing, for comparison to the effects of a prepared switch. Chapter 4 reports Experiment 4, which attempted to generalise the evidence for early, switch-induced processing delays beyond lexical tasks, by examining the effects of switching on an ERP marker of processing of facial emotion.

Whereas locating switch induced delays with respect to response selection and other processes may rule out certain variants of the theories considered above, it is not sufficient to distinguish between TSR-based and conflict-based accounts of the residual cost. Three experiments (reported in Chapter 5) further investigated the source of the post-stimulus switch-related negativity, generally assumed to be the neural correlate of the residual switch cost (e.g., Nicholson et al., 2005; Lavric et al., 2008) by asking whether this component could also be detected in single-task blocks when the irrelevant stimulus attribute in a bivalent stimulus had been associated with a competing task by previous training. Any such effect has to be attributed to relatively long-lasting associations between stimuli (categories of stimuli and/or individual stimuli) and potentially competing tasks and/or responses, not TSR or indeed transient task-set inertia as these could apply only to the initial trial of a single task block. Experiment 5 found that a bivalent stimulus whose irrelevant attribute was previously well-practised in a now-irrelevant task did indeed elicit an ERP component similar to the post-stimulus switch-repeat negativity seen in switching experiments, thus strengthening the conflict-based account of this component, and ruling out post-stimulus TSR as its source. Experiments 6 and 7 attempted to further clarify the nature of this long-term interference from the irrelevant task-set. Experiment 7 asked

whether it arises at the level of attentional selection. Experiment 8 (reported in Chapter 6) followed up an incidental finding in Experiment 1 that suggests an interesting relationship between set-level conflict and conflict between responding and withholding a response. One of the tasks in Experiment 1 used go-nogo response alternatives. To our surprise, we did not observe the usual and very robust ERP correlate of withholding a response — the Nogo-N2. Experiment 8 established that when exactly the same task is performed in a single-task experiment, the usual Nogo-N2 is observed. Hence, it is having to switch tasks that eliminates the NoGo-N2 enhancement. This sheds light on the relationship between task-level and response-level conflict in a task switching environment, and contributes to the debate between conflict detection and inhibition accounts of the N2 correlate of response-withholding.

Chapter 7 summarises the present findings and their implications for theories of the sources of the switch cost and gives some suggestions how to take this research further.

2

Partitioning the residual task-switch cost with ERPs

ABSTRACT

When people switch tasks, there is a cost in reaction time that, while reduced by preparation, is not eliminated. To determine whether the "residual" switch cost arises at the response-selection stage of processing, as several theorists assume, or earlier, we measured event-related potentials (ERPs) in two experiments with a task cue presented 800 ms before each stimulus. The stimulus was a letter string composed of blue and red letters. One task required the participant to read the letter string (semantic classification in Experiment 1, lexical decision in Experiment 2); the other task required a judgement of the symmetry of the arrangement of colours. In Experiment 1, the evolution of the effect of word frequency on the reading task ERP was delayed on a task-switch trial by a substantial fraction of the effect on RT. In Experiment 2, a task switch delayed the onset of the effect of lexical status on the ERP to about the same extent that it prolonged the RT. These ERP latency effects, together with PCA analyses, imply an early locus of the residual switch cost. In addition, effects of frequency and lexicality on symmetry task ERPs showed involuntary lexical activation modulated by a task switch in a manner consistent with task-set inertia. We propose that the main source of the residual switch cost is task-related *attentional* inertia. The findings also have implications for the automaticity of lexical access.

INTRODUCTION

It is generally harder to switch among several cognitive tasks than to continue to perform just one. A popular way to capture at least part of this multitasking overhead in the laboratory is to conduct a reaction time (RT) experiment in which, on each of a series of trials, a stimulus is presented, and the participant must perform one of several possible tasks. On some trials the task changes, on others it does not, other things being equal. Several such "task-switching" paradigms have been developed and extensively explored over the last two decades. (For reviews see Kiesel, Steinhauser, Wendt, Falkenstein, Jost, Philipp & Koch, 2010; Monsell, 2003; Vandierendonck, Liefooghe & Verbruggen, 2010).

Among the phenomena they reveal the most striking is the substantial cost to performance of a switch of task: the average RT for a correct response is longer (and there are usually more errors) when the task changes than when it is the same as on the previous trial.

The opportunity to prepare for a task before presentation of the stimulus generally reduces this *switch cost*, but does not eliminate it (Rogers & Monsell, 1995; Meiran, 1996). To manipulate preparation time unconfounded by the time elapsing since the previous performance of a task, a task-cuing paradigm can be used (Meiran, 2000): each stimulus follows the previous response by a standard interval, and a task cue precedes the stimulus by an interval which is independently manipulated to vary preparation time. For the simple classification or identification tasks typically used, as the cue-stimulus interval (CSI) is increased from zero, the RT switch cost reduces to an asymptotic *residual cost*, usually reached at a CSI of between half a second and one second (see Monsell & Mizon, 2006, for examples). This suggests two components to the switch cost: a part that can be mitigated by the exercise of active voluntary control (reflected in the reduction in switch cost, if there is time for preparation), and a part that cannot — the *residual cost*. We focus here primarily on this residual cost. As we review in more detail below, accounts of the residual cost tend to assume that what causes the extra difficulty on a switch trial, even after active preparation, is the application of the required set of stimulus-response rules in the face of the passive persistence (from the previous trial) of the rules associated with the competing task, and/or their involuntary reactivation (by the stimulus). This implies that the residual cost has its effect primarily on the "response-selection" stage of processing.

In the experiments reported in this paper, we used event-related potentials (ERPs) as a chronometric tool (Meyer, Osman, Irvin & Yantis, 1988) to test this assumption, by determining how early within the latent interval (between stimulus and response) processing is prolonged by a prepared switch. Attributing the residual switch cost to an increase in the duration of the response-selection stage implies a relatively late locus of the effect within the latent interval. To partition early and late processing stages we had participants switch between a task requiring lexical processing and a non-lexical task. We measured the effect of a task-switch on ERP markers of lexical processing: the effect of frequency in Experiment 1, the effect of lexical status (word versus non-word) in Experiment 2. To anticipate, the results of both experiments indicate that task switching

delayed lexical access by a substantial fraction of the total RT switch cost, suggesting an early locus of the residual cost. Moreover, the ERP effects of lexical frequency and status for the non-lexical task were consistent with a "task-set inertia" account of the residual cost.

Because we used tasks requiring lexical access in these experiments, the experiments are also informative concerning the "automaticity" of lexical access. The Stroop effect — the marked interference observed when a colour name is printed in a conflicting colour and participants must name the font colour (Stroop, 1935) — has classically been interpreted as showing that, for skilled readers, recognition of a familiar word and access to its meaning or phonology is "automatic", in the sense of being involuntary. But limits to the involuntariness of lexical access, as indexed by the Stroop effect, have also been demonstrated, as we review below. A related controversy, involving a somewhat different meaning of "automaticity", concerns the extent to which lexical access in a skilled reader requires generic cognitive resources – as indexed by the effects of a concurrent task. Is the process of lexical access invariant with respect to other concurrent task demands? In our experiments, when the participant was attempting to perform the non-lexical task, any activation of lexical representations would be counter-productive—tending to activate the inappropriate response. The occurrence of ERP markers of lexical access in the non-lexical task thus provides an index of the extent of involuntary lexical access. Their modulation by a task switch, on both lexical and non-lexical task trials, provides an index of the invariance of lexical processing as a function of task-control demands.

Theories of the (residual) task-switch cost, and its locus
In most task-switching experiments, two or more sets of S-R rules are defined so that for the *incongruent* stimuli — those to which a different response is made in the two tasks — the appropriate response would be ambiguous without the task cue. Stimuli mapped to the same response in both tasks are said to be *congruent,* stimuli affording a response in only one task are *univalent*. Competition between task-sets is manifest at two levels. Competition at the S-R level is indicated by a response congruence effect: responses are slower and less accurate to incongruent than to congruent stimuli (Rogers & Monsell, 1995; Goschke, 2000, Meiran & Kessler, 2008). Competition at the task-set level is indicated by longer RTs to congruent stimuli — for which mere S-R activation via the irrelevant task-set

should facilitate response selection, than to univalent stimuli — which should activate neither the irrelevant task-set nor its responses (Rogers & Monsell, 1995; Aron, Monsell, Sahakian & Robbins, 2004, Steinhauser & Hübner, 2007) and by other evidence (Elchlepp, Lavric, Mizon & Monsell, 2011; Monsell, Taylor & Murphy, 2001).

Many theorists (though not all – see Logan & Bundesen, 2003; Schneider & Logan, 2005) assume that in the task-cuing paradigm, the participant interprets the cue and actively engages the appropriate task-set. If the task changes, this requires a process of *task-set reconfiguration* (TSR), which may include re-allocating attention and/or activating the appropriate set of S-R rules and/or suppressing the previously active set (Rogers & Monsell, 1995). If the task is the same as on the previous trial, participants might or might not actively reinforce the existing task-set, but *re*-configuration is not required. The reduction in switch cost with preparation suggests that a motivated participant can, if time permits, carry out some part of TSR before the stimulus arrives. Doing so reduces the average RT because it (a) saves time that would otherwise be consumed by TSR after the stimulus onset, (b) reduces competition from the irrelevant task-set (response congruence effects sometimes do, and sometimes do not reduce with preparation; see Monsell & Mizon, 2006); (c) avoids the dual-process cost of deciding on and engaging the relevant task-set while performing the task-specific processes required; (d) some combination of these.

Clearly whatever is accomplished by task-set reconfiguration on a switch trial does not completely disable the other task-set(s). On task-repeat trials, competition from the irrelevant task-set is still evident in S-R level and task-set level interference, although such interference is usually smaller than on a task-switch trial (e.g., Rogers & Monsell, 1995; Goschke, 2000). A substantial congruence effect can still be seen several trials after a switch when the transient after-effects of a task switch are no longer detectable in overall performance (Monsell, Sumner & Waters, 2003). Indeed, it may be non-optimal to suppress the irrelevant task-set completely, as it must be kept available for reactivation when the task switches again. The need to maintain multiple task-sets in an available state provides a possible reason for the "mixing cost", the longer RT on task-repeat trials in a mixed-task block than in a pure-task block (Jersild, 1927; Allport Styles & Hsieh, 1994).

The residual switch cost clearly indicates that advance preparation on a task-switch trial does not achieve the degree of task-readiness manifest on task-repeat trials. The literature offers a number of theories about why this is so, which we now summarize in turn, focusing on what each theory has to say about which processing stage(s) is/are prolonged on a switch trial:

Exogenously triggered completion of reconfiguration. Rogers and Monsell (1995), having attributed the part of the switch cost that was eliminated by preparation to a TSR process, suggested the residual cost might be due to a second stage of TSR activated only upon presentation of the stimulus. Rubinstein, Meyer and Evans (2001) speculated that the task-goal could be retrieved prior to the stimulus, but retrieval of the S-R rules only after stimulus onset. Such an additional component of TSR would need to be largely completed before response selection begins, so that the S-R rules appropriate to the current task are more active than the alternative set(s). Hence this theory implies an early locus of the residual cost.

Task-set inertia. Allport et al. (1994) suggested that the task-switch cost resulted from "a form of pro-active interference from features of the task set implemented in previous tasks" (p.421), which they labelled "task set inertia"; this persistence of a previous task-set conflicting with the now-appropriate task-set results in "additional time for the system to settle to a unique response decision (or response retrieval) after the next imperative stimulus has arrived" (p.437). Initially this was offered as an exhaustive account of the switch cost, but when it was found (Meiran, 1996, Rogers & Monsell, 1995) that the (mean) switch cost seemed to have two components — one eliminable by active preparation, one not — the idea of "inertia" seemed appropriate to account for the latter component — the residual cost. Allport et al. (1994) initially conceived of task-set inertia as having a persistence of the order of minutes, but evidence of long-term effects of prior encounters (Allport & Wylie, 2000) seem better dealt with by the idea of associative activation of task-sets by stimuli proposed by Waszak, Hommel and Allport (2003) and discussed below. Hence the core idea of task-set inertia is that persisting activation of task-set activation and/or inhibition from the most recent trial, or last few trials, is a major source of conflict and the (residual) switch cost (Altmann & Gray, 2008; Gilbert &

Shallice, 2002; Mayr & Keele, 2000; Meiran, Chorev & Sapir, 2000, Yeung & Monsell, 2003).

The idea of task-set inertia can incorporate both persisting activation of the previous task-set and persisting inhibition of the now-appropriate task (Meuter & Allport, 1999; Masson, Bub, Woodward & Chan, 2003). The puzzling observation of larger costs for switching to the stronger of two tasks was attributed by Allport et al. to the difficulty of overcoming the substantial inhibition that had to be applied to the stronger task to enable performance of the weaker task (see also Meuter & Allport, 1999). But Yeung and Monsell (2003) were able to model the paradoxical asymmetry (and manipulations that reversed it) with an interaction between persistent task-set activation and "just-enough" adjustment of top-down control biasing, without using inhibition (though they could doubtless have used persistence of inhibition instead or as well). More suggestive of an inhibitory component of task-set inertia is the phenomenon originally labelled "backwards inhibition" (Mayr & Keele, 2000) but more neutrally termed the "N-2 repetition cost": the finding that RT is longer on the final trial of an ABA task sequence than of a CBA sequence (see Koch, Gade, Schuch & Philipp, 2010; Mayr, 2007 for review). The inertia account is that the inhibition applied to suppress task A in favour of task B on the second trial of the ABA sequence persists, causing extra difficulty when A is required again on the third trial. There has been debate about the decay of task-set inertia. Meiran et al. (2000) argued that the effects of varying the response-stimulus interval independently of cue-stimulus interval suggested initially rapid spontaneous decay of task-set inertia with time, but Haroufchin, Philipp and Koch (2011) reinterpret this evidence.

For present purposes, the critical question is which stage of processing might be prolonged by task-set inertia. In principle there could be inertia at any level of a task-set, but both Allport et al. (1994) and Yeung and Monsell (2003) assumed that the locus of the conflict produced by task-set inertia was in response selection. Other loci are certainly plausible. Masson et al. (2003) observed greater difficulty switching from colour naming to word naming when the stimulus whose colour was named was a word rather than a string of asterisks and argued that this reflected persisting inhibition of the word-reading pathway. Yeung, Nystrom, Aronson and Cohen (2006) conducted an fMRI study in which participants switched between classifying the face or the word in a composite of the two. In

a separate part of the experiment, they located in the same participants brain regions (in right fusiform gyrus and left inferior temporal gyrus) selectively activated by face and word-processing, respectively, and showed that in the switching blocks activation of its region predicted the RT cost of switching *away* from that task. As well as providing a neural correlate of task-set inertia, this is more suggestive of persisting activation of a whole domain-specific processing pathway than of S-R rules per se.

Response-contingent reconfiguration. While preparation helps, the residual cost implies that task-set reconfiguration is incomplete until the new task has been performed at least once. Meiran (2000, Meiran, Kessler, & Adi-Japha, 2008) has argued that while attention can be redirected to a different dimension during the preparation interval, removing the cost to processing of inappropriate attentional orientation, it is only when the participant actually responds that response-set biasing (changing the meaning of the response set) can be accomplished – hence the residual cost.

A different claim about the importance of making a response was made by Schuch and Koch (2003) on the basis of an observation since replicated and extended in a number of studies (see Los & Van der Burg, 2010, for a review). On some trials they presented a "no-go" signal along with the target stimulus, telling the subject to withhold a response. This eliminated the switch cost on the following trial. They argued that "when switching from one task to another in typical task-switching paradigms, a conflict arises between the previous and the current category–response rules, and it becomes necessary to inhibit the previous set of rules", (p.101). That is, even after full pre-stimulus preparation, conflict arises after the stimulus, and a task-set suppression process must be applied to resolve it and ensure that the appropriate response is produced. Until that suppression has been applied, task-set reconfiguration is not complete and does not "stick". According to Koch and colleagues, this suppression process is also the source of the n-2 repetition effect. This is essentially an inhibitory variant of the task-set inertia hypothesis (i.e. inhibition of a task-set on the previous trial persists) coupled with the assumptions that effective inhibition can be applied only post-stimulus (not during preparation), and is applied specifically during response selection, not before. A corollary of the latter assumption is that the locus of the conflict triggered by task-set inertia is the response selection process — a late locus.

Associative reactivation of a competing task-set. Waszak et al. (2003) proposed that switch costs arise, not because task-set activation carries over from the previous trial, but because the stimulus reactivates (retrieves) task-sets with which it was previously associated. Manipulating the associative history of particular stimuli (i.e. which task context they had previously appeared in) they found slower responses to stimuli presented, many trials before, in the context of the competing task. An attractive feature of this theory is that it provides a rationale for why there are long-term effects (they arise from associative learning, not transient persistence of activation). It also potentially offers an account of why advance preparation is only partially effective: as in the Schuch and Koch account, it may not be possible to suppress the source of conflict until conflict happens, and it is only after the stimulus has reactivated the competing task-set that conflict happens. However, it should be noted that for the theory to provide an account of the residual switch cost, associative activation must have a greater effect on switch than on repeat trials. And although everyone who has looked for an effect of prior association with a competing task on RT has found it, the effect frequently does not interact with the effect of task switch/repeat (see Monsell & Mizon, under revision). Moreover, while the theory was originally proposed by Waszak et al. as an alternative to task-set inertia, Waszak et al. (2005) acknowledge that task-set inertia is also required to explain why switch trials are particularly vulnerable to the effects of task-set reactivation (when they are).

Which processing stage might be slowed by reactivation of a competing task set? Any component of a task-set – attentional settings, S-R rules, etc — could in principle be reactivated by the stimulus. But, as for task-set inertia, the assumption seems to have been that the response-selection process is the primary locus.

Probabilistic failure to engage the task-set De Jong (2000) proposed that both the RISC effect and the residual cost were explained by just one all-or-none TSR process, that sometimes "failed to engage", so that preparation was either completely effective (performance as good as on a task-repeat trial) or completely ineffective (performance as bad as on an unprepared switch trial). The residual switch cost arises from the average of these two outcomes weighted by their probability. The main evidence favouring this account is that (in the alternating runs paradigm, where task-repeat trials show no effect of preparation) RT distributions on prepared switch trials could be modelled as a mixture of RTs from unprepared switch and prepared repeat trials (De Jong, 2000; Nieuwenhuis &

Monsell, 2002). The main puzzle is that long preparation intervals, which should allow multiple attempts to engage the task-set, still leave a residual cost in highly motivated participants. This theory appears to make no particular claims about the processing locus of the residual cost.

Thus far, we have reviewed a number of accounts of the residual cost of a task-switch, of which the most popular is some form of task-set inertia, whether persisting activation (Yeung & Monsell, 2003) or persisting inhibition (Schuch & Koch, 2003) or both, possibly coupled with associative reactivation of the task-set (Waszak et al., 2003). While these accounts do not all logically require that the locus of the residual cost is response-selection, that has often been the assumption made (e.g., Allport et al., 1994; Meiran, 2000; Yeung & Monsell, 2003), and this locus appears to be a necessary assumption of the Schuch and Koch (2003) account. Hence it is important to establish which processes are in fact prolonged in duration by a prepared switch of tasks. To do this, we used event-related potentials to localise the effect of a task-switch within the reaction-time.

The experiments
In principle, event-related potentials provide a chronometric tool for splitting up the reaction time (or at least the average reaction time) into the durations of underlying processing stages (Meyer et al., 1998), and partitioning any effects of an experimental variable, such as task-switch versus -repeat, amongst them. To do this we must identify ERP components, or markers detectable in the ERPs, that can be confidently tied to processes of interest. Further difficulties include the variability of process durations, the possibility of overlapping process durations, and the need to average over many trials to extract a clear ERP signal from the noise. Hence such chronometric applications of ERP remain relatively rare. However, given a suitable marker, one should at least be able to distinguish between the prolongation of "early" and "late" processes by a task-switch.

To engage in this chronometric enterprise one needs a task for which there is some agreement on the constituent processing stages, a variable known to affect one such stage, and a clear marker in the ERP of when it has its effect. For this reason we used as one of the tasks in our experiments a lexical access task: semantic categorisation (living/non-

living) in Experiment 1, lexical decision (word/non-word) in Experiment 2. We assume (along with most psycholinguists) that the successive processes underlying semantic categorisation are:

pre-lexical encoding of the stimulus in the form of an orthographic representation of the identity and order of its constituent letters;

lexical access, which comprises *lexical identification* —matching of the orthographic representation to stored word forms, and *semantic activation* — activation of the meaning or semantic features associated with the best-matching form(s);

response selection (or decision) — comparison of the activated meanings or semantic features to some template of the response categories or their boundary and selection of one of the two response categories;

response execution — translation of the abstract response category into an overt motor response.

Note that we do not assume these processes or sub-processes to be discrete: they may overlap, and lexical identification and semantic access may interact.

The processes required for the lexical decision task are similar. Although finding a good match in the lexical identification process is logically sufficient for a word decision, semantic activation may provide an additional cue (because only words have meanings). Response selection for lexical decision involves discriminating the states of activation of lexical/semantic representations triggered by words and non-words.

Frequency of use of a word in the language has a considerable - and similar - impact on both semantic categorisation time and lexical decision time (Monsell, Doyle & Haggard, 1989). Although there has been some argument about the locus of the frequency effect (Balota & Chumbley, 1984; Monsell et al., 1989), all models of lexical access incorporate a mechanism for ensuring more rapid matching or activation to more familiar word forms and more rapid activation of their meanings (Norris, 2006). The effects of frequency can also be seen early in the ERP waveform. Sereno, Rayner and Posner (1998) reported a larger N1 with a concurrent left anterior positivity for low frequency (LF) than for high frequency (HF) words between 132–192 ms. More negative amplitudes for LF than for HF words were observed by Proverbio, Vecchi and Zani (2004) between 150–190 ms and between 140–200 ms by Dambacher, Kliegl, Hofmann and Jacobs (2006). King and Kutas

(1998) found what they refer to as "frequency sensitive negativity" (FSN), which has a left frontal topography and peaks at ~280 ms for HF and ~335 ms for LF. And later in the ERP it is well-established that N400 amplitudes are larger for low compared to high frequency words (Barber & Kutas, 2007). The earliest of these effects are controversial, but it appears that from 200 – 300 ms after visual presentation of a word, ERP markers of effects of word frequency can be reliably detected.

The only previous attempt to partition task-switch costs using ERPs of which we are aware is Hsieh and colleagues' (Hsieh & Yu, 2003; Hsieh & Liu 2005; Hsieh, 2006) use of P3 and lateralised readiness potentials (LRPs). Their finding (Hsieh, 2006) was that P3 (which they regard as a marker of stimulus identification) was not delayed by a task-switch, while the onset of the LRP (measured from stimulus onset) was delayed by a task-switch, while the LRP onset relative to the response was unaffected. Given the standard view that LRPs, which begin to build up about 150 ms before the response is detected, correspond to motor activation of the corresponding hand – i.e. response execution, this finding appears merely to confirm the expectation of almost all theorists that, when the same response set is used for both tasks, task switching prolongs response selection or earlier processes. The failure to find a delayed P3 might be taken to suggest that processes earlier than response selection are not delayed. However, P3 is sensitive to a number of factors, e.g., saliency or frequency of a target, and its magnitude may be modulated by switching per se. Even if one found a delay in P3 one would not be able to uniquely specify which process is delayed. Our approach is somewhat different. We used the onset of frequency effects as a difference in processing which is specific to a processing stage in a task of interest and orthogonal to switching. A delay in the onset of the frequency effect on a task-switch trial would suggest that a task-switch prolongs pre-lexical encoding or an early phase of lexical access.

Choice of the other task. The second task was chosen to minimize the likelihood that significant reorientation or redistribution of spatial attention would be required when switching between that task and the lexical task. For example, attention to a single letter in a word produces a different gradient of spatial attention to attention to the whole word (LaBerge, 1983), as well as modulating the Stroop effect (Besner & Stolz, 1999). Processing in extrastriate cortex indexed by P1/N1 is substantially modulated by shifts in spatial attention (e.g., Hopf & Mangun, 2000). Hence we needed a second task that would

require a distribution of attention over the whole letter string similar to that induced by word recognition (LaBerge, 1983). To this end, the stimuli were three to seven letter words (in both experiments) and non-words (in Experiment 2), each of whose letters was printed in red or blue. For the other task, participants had to decide whether the colours were distributed symmetrically (e.g. RBRBR) or asymmetrically (e.g. RRBBR) about the center. To perform the lexical task in each experiment required attention to orthographic properties of the letter string (letter identity and order), and the colouring of the letters was irrelevant. To perform the symmetry task required attention to the spatial distribution of colours across the string, and the lexical content was irrelevant.

Lexical activation during performance of the symmetry task
Processing of lexical content was not merely irrelevant to performance of the symmetry task; it was non-optimal, as it could activate inappropriate responses. Evidence of involuntary word recognition from the Stroop task nevertheless led us to expect to see ERP markers of lexical access on the symmetry task trials, and these are of interest for two reasons.

First, according to the task-set inertia account, task-set activation and inhibition carry over to the next trial. It follows that one should see more evidence of processing specific to the irrelevant task (in this case lexical processing on symmetry task trials) on switch trials. So far the only neurophysiological evidence to support this prediction comes from Yeung et al.'s (2006) fMRI study, as reviewed above: greater activation of the face area was associated with greater difficulty of switching to the word task, and of the word area with greater difficulty of switching to the face task. However, with a CSI of only 450 ms, it is not clear that their RT cost was fully "residual", and the fMRI BOLD signal was generated by sequences of four trials in each task. The temporal precision of ERP allows us to look for trial-by-trial modulation of processing appropriate to the wrong task.

More generally, the occurrence and modulation of lexical access on the symmetry task trials is of relevance to the controversial issue of the involuntariness of word recognition. The Stroop effect has been taken to imply that lexical identification and semantic activation are automatic (Stroop, 1935). One limitation to this claim is that the Stroop effect is substantially attenuated if the colour named and the word are spatially

separated (Kahneman & Henik, 1981) or if the participant attends to a single letter rather than the whole letter string (Besner, Stolz & Boutilier, 1997). However, with an appropriate distribution of spatial attention over the letter string (LaBerge, 1983) involuntary access may still be the default assumption. Taken seriously, this would imply that provided the locus and distribution of spatial attention is appropriate, lexical identification and semantic access will occur unmodified by whether the current trial requires it or not. We would then have to suppose task-set reconfiguration works by making or unmaking the connection between semantic activation and response-selection, not by some earlier modulation. On the other hand, it is also widely assumed that people can attend to dimensions as well as locations and objects (Treisman, 1969; Müller, Reimann & Krummenacher, 2003); hence an alternative possibility is that a switch away from the lexical task will modulate the degree to which orthographic properties are attended and lexical representations activated. The amplitude of frequency- or lexicality-related effects in the ERP on the symmetry task trials, and their modulation by task-switching, should tell us whether lexical access is automatic in the former strict sense, or modulated by non-spatial attention.

Does lexical access require resources? A different sense of the idea of "automaticity" of word recognition is implied by the issue of whether lexical access requires generic cognitive capacity or resources, as tested by combining performance of a lexical task with performance of another capacity demanding concurrent task. Lien, Ruthruff, Goodin and Allen (2008) used the psychological refractory period paradigm (PRP) with lexical decision as the second of two tasks and investigated word frequency effects on event-related potentials (ERPs) as an online assessment of lexical access. Attenuation of lexical access was seen in a diminished N400 and the effects of word frequency on P3 were nearly abolished when stimulus onset asynchrony (SOA) was short (100 or 300 ms versus 900 ms). They concluded that lexical access requires central resources. Reynolds and Besner (2006) also used the PRP paradigm but with reading aloud as the second of two tasks. They found that when SOA was short an early component of lexical processing (lexical encoding) was uninfluenced by processing of the first task suggesting automaticity of this process. Assembling phonology, on the other hand, and lexical contributions to phonology encoding showed additive effects with SOA suggesting they do use central attention.

Vachon & Jolicoeur (2011) used the attentional blink paradigm in which seven stimuli were presented in short (117ms) succession (rapid serial visual presentation, RSVP) including two target stimuli which required a response. Target 2 could follow target 1 immediately (lag=1) or with lags of 3 or 7. Each mini-block was preceded by a context word and on half of the blocks subjects judged both target words as to whether they were related to the context word or not (non-switch condition). On the other half of the blocks subjects judged whether the two digits surrounding the target 1 word were the same or different; for target 2 they always performed the context judgment (switch condition). Even when target 2 followed target 1 immediately, N400 amplitudes (as derived by subtracting trials related to the context word from unrelated ones) were uninfluenced by the attentional blink as long as both targets required the semantic judgment. Introducing a task-set switch (digit to semantic judgment), however, reduced and delayed N400 amplitudes, suggesting an impairment of semantic processing of target 2. This indicates that semantic processing and task-set reconfiguration could not be carried out in parallel which in turn implies that semantic processing of a word is not automatic.

The controversy with regards to the automaticity of lexical access could suggest possible reasons why switching might slow early processing during performance of the lexical task: on switch trials the re-allocation of resources might be incomplete, or resources might be concurrently consumed by a reconfiguration process (although most of this should be completed during the CSI when time to prepare is long).

Experiment 1

The stimulus was a word whose letters were coloured red or blue. The participant was instructed, by a visual cue, either to classify the word as referring to a living or nonliving object, or to classify the distribution of colours over the letters as symmetrical or asymmetrical. The main questions addressed were: (1) is the evolution of the frequency effect in the ERP on the semantic categorisation trials delayed on a switch trial in such a way as to suggest that a task-switch prolongs early (lexical or pre-lexical) or later (response selection) processes? (2) Are markers of lexical access detectable on symmetry task trials, and are they amplified by a task-switch as a task-set inertia account suggests?

The symmetry task was designed as a go/nogo task in the hope of using the N2 component in the ERP as a marker of completion of the symmetry judgment. Subjects responded to asymmetrically coloured words with a key press and withheld the response for symmetrically coloured ones. A substantial literature shows that in go/no-go discrimination tasks N2 and the longer-latency anterior-central P3 are both amplified on a no-go trial. Both have been proposed to reflect inhibition of the pre-potent response (Eimer, 1993; Lavric, Pizzagalli & Forstmeier, 2004); alternatively, N2 might reflect conflict between that activation of that response and withholding it (Nieuwenhuis, Yeung & Cohen, 2004). Either way, since the symmetry judgment must largely precede the decision to respond or withhold the response the N2 may help to localize the detection process within the RT. However, to anticipate the outcome, it turned out that switching tasks eliminated the N2, so it could not be used as a marker of anything.

Although the focus of the present experiment was on post-stimulus ERPs we also examined ERPs during the cue-stimulus interval for evidence of active preparation for a task switch. Several switch-specific modulations of the pre-stimulus waveform have been found in preparation intervals (Karayanidis, Jamadar, Ruge, Phillips, Heathcote & Forstmann, 2010, for review) including a protracted posterior positive deflection starting from ~400 ms or more after the cue/previous response (e.g. Karayanidis, Coltheart, Michie & Murphy, 2003; Lavric, Mizon & Monsell, 2008; Rushworth, Passingham & Nobre, 2002), an anterior negativity in the same latency range (e.g. Astle, Jackson, & Swainson, 2008; Lavric et al., 2008), a longer-latency anterior-central negativity (Tieges, Snel, Kok, Wijnen, Lorist, & Ridderinkhof, 2006; Tieges, Snel, Kok, Plat & Ridderinkhof, 2007), and an early anterior positivity (Lavric et al., 2008; Rushworth et al., 2002). The first two components have been linked to advance task-set reconfiguration, because their amplitude co-varied with the effectiveness of preparation over trials (within subjects), as well as over subjects (Lavric et al., 2008; Elchlepp et al., 2011).

METHOD

Participants

Eighteen right-handed students from the University of Exeter (15 female, 3 male) aged between 18 and 38 (M=21) received two course credits for participation plus a monetary performance bonus (maximum £4 — see below). Participants gave informed consent

following the guidelines set by the University of Exeter School of Psychology ethics committee.

Stimuli and Procedure

On each trial, a word of 3-7 letters (subtending 1˚- 2.5˚ horizontally) was displayed in the centre of the screen in a non-proportionally spaced font (Lucinda Console), with some letters coloured in blue and some in red, and the participant performed one of two tasks. The "semantic" task was to categorise the word as referring to a living or non-living object by pressing the right or left arrow key; the two categories were equiprobable. The "symmetry" task was to determine whether the two letter colours were distributed asymmetrically or symmetrically relative to the middle of the word (and screen). For asymmetrically coloured words participants made a "go" response with a key press (left arrow key for half of the participants and right arrow key for the other half). Symmetrically coloured words required withholding any response for 1500 ms ('Nogo' trials). In line with the conventional Go-Nogo ERP paradigm, the probability of Nogo trials was lower than that of Go trials (37.5% and 62.5%, respectively).

The sequence of tasks was unpredictable, with task identity indicated on every trial by one of four cues (two for each task). A cue appeared 800 ms before the stimulus and remained on the screen with the stimulus until a response was made. Each cue was a pair of small shapes displayed above and below the word's centre to provide a midline marker and fixation as well as specifying the task, and in close proximity to the word to minimize eye movements (see Figure 2.1B). Each possible assignment of pairs of cues to tasks was used for 6 participants. To avoid confounding cue and task changes the cue changed on every trial. The task changed on a random third of trials; this relatively low probability was intended to discourage subjects from preparing for a possible switch prior to cue presentation (cf. Monsell & Mizon, 2006). On all the trials in the semantic task and on Go trials in the symmetry task, the stimulus was displayed until a response was made, timing out at 2500 ms; on Nogo trials the stimulus was presented for 1500 ms. If a key press was detected on Nogo trials, or the wrong key or no key was pressed on other trials, the word "ERROR" was displayed for 1500 ms. Otherwise, the interval between each response and the cue for the next trial was 800 ms (see Fig. 2.1A).

A. a trial

Response to Stimulus Interval 1600 ms

Blank: 800 ms   Cue: 800 ms   Stimulus
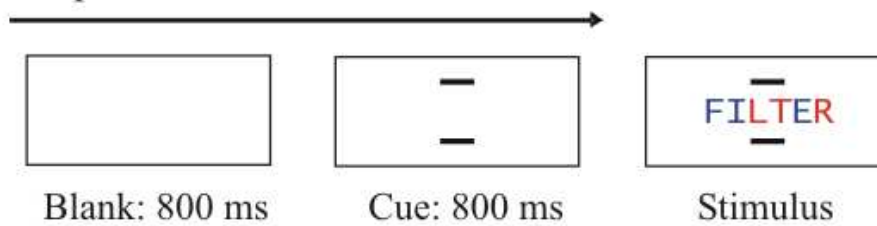
B. Cues with examples of symmetric and asymmetric stimuli

Figure 2.1 *Trial sequence, cues and stimuli*

Of the 384 word stimuli used, half referred to living and half to non-living objects. Half of each subset were high frequency nouns (HF: >10/million, mean log frequency 1.3), and half low frequency nouns (LF: <5/million, mean log frequency 0.3), selected using the CELEX database of frequencies in British English (Baayen, Piepenbrock, & van Rijn, 1993). In each of those four subsets 37.5 % of the words had a symmetrical pattern of colours. Each word was presented three times throughout the experiment, always in the same task, with the cue assigned randomly. The assignment of word stimuli to tasks was counterbalanced over subjects, as was the combination of occurrence of the word (1st, 2nd or 3rd) with task transition (switch versus repeat). In particular, a third of the subjects saw a subset of words (which contained equal numbers of living/non-living by LF/HF words) first on switch trials (and for the second and third time on repeat trials), another third saw those words on switch trials on the second occurrence, and the remaining third of subjects saw them on switch trials at third occurrence during the experiment. Hence, words could be in one of 12 sets (living/non-living x LF/HF x switch at 1st/2nd/3rd occurrence) and these sets were matched for word length distribution. Furthermore, mean log word frequency for symmetrically and asymmetrically coloured words was matched within high and low frequency sets. Subject to these constraints, the order of trials was randomized anew for each participant.

The EEG session was preceded by practice comprising four single-task blocks of 24 trials each (two blocks per task), one block of 24 trials of learning cue-task associations, and two 49-trial blocks like the experimental blocks. In the practice session, Go trials timed out after 5000 ms. Following practice, participants performed 24 blocks of one warm-up plus 48 trials, during which EEG data were acquired. During these blocks, there were 96 switch and 192 repeat trials for each task and frequency band.

Participants were instructed to use the cue to prepare for the upcoming task. To encourage effective preparation a score (mean RT/10 + errors*5) was computed for each block and a bonus payment was made for blocks on which the score was lower than a running average of previous blocks.

EEG and ERPs

The EEG was sampled continuously at 500 Hz with a bandpass of 0.016-100 Hz, the reference at Cz and the ground at AFz using 64 Ag/AgCl active electrodes (ActiCap, Brain Products, Munich, Germany) connected to BrainAmp amplifiers (Brain Products, Munich, Germany). There were 61 electrodes on the scalp in an extended 10-20 configuration, one on each earlobe and one below the right eye. Electrode locations were adjusted using a CMS ultrasound digitizer (Zebris Medical, Isny, Germany) and their impedances kept below 10kΩ. Following offline filtering with a 20 Hz low-pass filter (24 dB/oct) and re-referencing to the linked ears, the EEG was segmented into a 1600 ms epoch, time-locked to the cue and baseline-corrected relative to the average amplitude of the 100 ms preceding the cue. This baseline was chosen because the pre-stimulus baseline contains large switch-repeat differences, which would distort the switch-repeat comparison of post-stimulus ERPs. Segments associated with incorrect responses were discarded, as were segments following errors and segments referring to the first trial of a block (because the latter two could not be classified as switch/repeat trials). The resulting segments were visually inspected for ocular, muscle, movement and other artifact and segments containing such artifact were removed. Criteria for removal were either of the following: (1) amplitudes exceeded a threshold of ±50μV, (2) the waveform showed the clear shape and duration of an eye-blink artifact, was largest in frontal channels where it had a positive polarity, (3) large drifts in at least several channels, (4) high frequency artifact greatest in temporal channels suggestive of muscle artifact, and (5) unusually large amplitudes in the alpha

frequency band.[1] The remaining EEG segments were averaged for every participant and experimental condition.

To identify components underlying the ERP we used temporal principal components analysis (PCA) (Donchin & Heffley, 1978). The PCA was run on an electrode (62) x condition (4 levels) x subjects (18) x time-points (400 for the CSI, and 375 for the post stimulus interval) matrix of cases (observations), with time-points as variables. We ran PCAs for the pre-stimulus interval to detect switch related preparatory activity (as in Lavric et al, 2008) and any differences in preparation for the two tasks. Our main interest, however, is in switch-related effects and delays in the post-stimulus ERP. These we expected to be task-specific, so for this interval separate PCAs were run for the two tasks: for the semantic task with conditions switch-repeat by frequency (LF, HF), and for the symmetry task- with conditions switch-repeat by Go-Nogo and switch-repeat by frequency. All PCAs were performed on the covariance matrices and their solutions were Varimax-rotated to yield uncorrelated temporal components; the criterion for component extraction was that of eigenvalue ≥1; only components accounting for at least 2% of the variance were subjected to statistical analyses. To identify components sensitive to experimental manipulations ANOVAs were run on the scores of the PCA components, which represent the amplitude of components at each electrode for each condition and subject. To assess potential interactions of the experimental conditions with scalp regions minimizing the number of levels of that factor, amplitudes were averaged for groups of electrodes along the anterior-posterior (4 levels) and laterality (3 levels) dimensions; region and laterality were factors in the ANOVA (see Figure 2.2). Significance levels were adjusted using the Huynh-Feldt correction for violations of sphericity (but unadjusted degrees of freedom are reported).

ERP latency analysis

The primary aim of our experiment was to determine whether and by how much certain landmarks in the ERP are delayed on switch trials, to provide a basis for partitioning of the RT switch cost among different stages of processing. To identify such landmarks, we computed (separately for switches and repeats) the ERP difference wave corresponding to the manipulation associated with a process (or set of processes) expected to be delayed. In

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[1] These criteria for artifact rejection were applied to all ERP studies of this thesis and will hence not be described again in detail later.
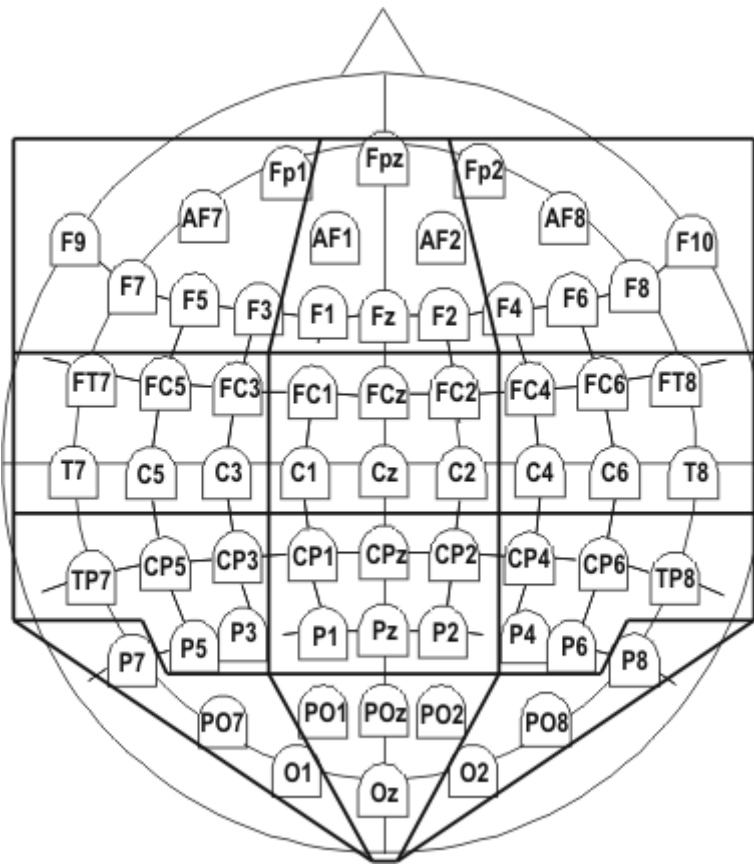
Figure 2.2 *Electrode arrangement and regions*

Experiment 1, the frequency difference wave was computed by subtracting the amplitude of the ERP for high-frequency words from the ERP for low-frequency words. We then compared the latency of peaks (minima and maxima) in the difference waves for switch and repeat trials. To circumvent the issue of selecting individual electrodes for this comparison, latency calculations were performed on the Global Field Power (GFP) of the difference wave, which is the square root of the mean of all scalp channels' squared amplitudes. (See Hamburger & van d. Burgt, 1991 on the superiority of GFP for latency analyses).

To assess any such latency delays statistically, we needed to determine not only the mean but also the variance over subjects of the position in time of a given landmark. Since individual subjects' waveforms or difference waves are typically too noisy to unambiguously locate every landmark seen in the grand average, we used the "jackknifing" method (Miller, Patterson & Ulrich, 1998). In accordance with this procedure, given 18 subjects as well as the grand average, a further 18 average waveforms and difference waves were computed each omitting one subject's data. A peak or inflexion was estimated in the

same way for each of these averages, and the standard deviation of its shift in temporal location, between switch and repeat trials, computed over the 18 sub-averages. From this, an estimate of the variability of the shift in location of the landmark in time over subjects could be derived using Miller et al.'s formula for computing the standard error and hence the t-statistic. This formula was developed to appropriately estimate the standard error in a within-subjects design. Only t-values corrected (as indicated with the label t_c) with this formula are reported.

RESULTS AND DISCUSSION

Behavioural results

Mean correct RTs and error rates for all combinations of switch/repeat, task, frequency and symmetry are given in Table 2.1[2] (see also Figure 2.3). (The first trial of each block and trials preceded by errors were excluded from the behavioural and ERP analyses.) For the symmetry task, only Go trials (62.5% of trials) have RTs. A switch (2) by task (2) by frequency (2) ANOVA on RTs found significant main effects of switch, $F(1, 17) = 33.72$; $p < 0.001$, task, $F(1, 17) = 22.87$; $p < 0.001$ and frequency, $F(1, 17) = 7.01$; $p < 0.05$. Responses were slower on switch trials than on repeat trials, faster for high frequency than for low frequency words and faster in the semantic task than in the symmetry task. The mean and standard error of the switch cost for the semantic task were 50 ± 12 ms, and for the symmetry task 52 ± 13 ms. The effect of frequency (LF versus HF) was larger in the semantic task (30 ms) than in the symmetry task (7 ms), though this difference did not reach statistical significance, $F(1, 17) = 3.23$; $p = 0.09$.

The symmetry factor could not be included in the preceding ANOVA because in the symmetry task, symmetrically coloured words were not responded to (Nogo trials). A separate ANOVA was run for the semantic task including only the factors switch, symmetry and frequency. Apart from the expected main effects of switch, $F(1, 17) = 16.48$; $p < 0.001$, and frequency, $F(1, 17) = 17.37$; $p < 0.001$, a reliable effect of symmetry, $F(1, 17) = 4.45$; $p = 0.05$ was found. Symmetrically coloured words (which required withholding a response in the other task) were responded to more slowly (852 ms) than asymmetrically coloured words (833 ms), suggesting some interference from the irrelevant task.

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[2] Tables can be found in the appendix of the chapter
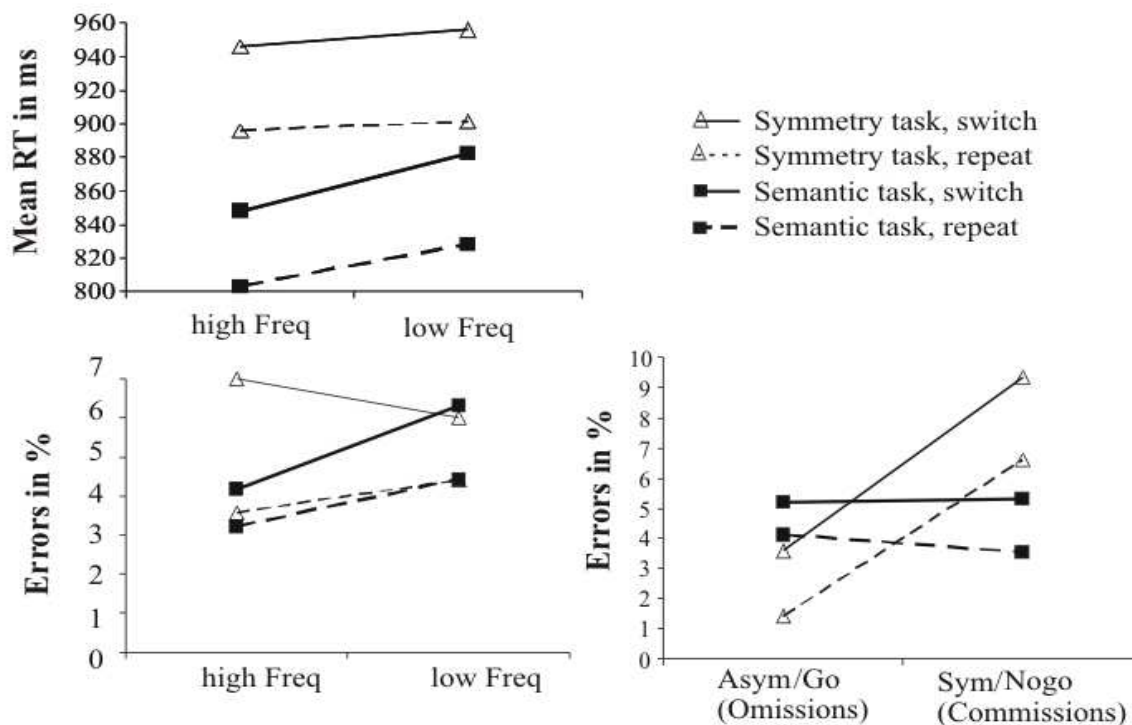
Figure 2.3 *RTs and error rates of experiment 1*

An ANOVA on the error rates including the factors switch, task, frequency and symmetry found reliable effects of switch, $F(1, 17) = 21.3$; $p < 0.001$, frequency, $F(1, 17) = 7.17$; $p < 0.05$, and symmetry, $F(1, 17) = 18.75$; $p < 0.01$, a reliable interaction between task and symmetry, $F(1, 17) = 21.8$; $p < 0.001$, and a marginally reliable three-way interaction between switch, task, and frequency, $F(1, 17) = 3.29$; $p = 0.087$. To investigate these effects in more detail, separate ANOVAs were run for the two tasks. For the semantic task, switch cost ($1.5 \pm 0.4\%$), $F(1, 17) = 10.66$; $p < 0.01$ and frequency effects ($1.6 \pm 0.6\%$), $F(1, 17) = 9.91$; $p < 0.01$ were reliable. For the symmetry task, a reliable switch cost ($2.6 \pm 0.8\%$), $F(1, 17) = 10.11$; $p < 0.01$ and effect of symmetry (Nogo versus Go, $5.5 \pm 1.1\%$), $F(1, 17) = 25.16$; $p < 0.001$ were found, the latter reflecting more commission errors on Nogo trials (8%) than incorrect or omitted responses on Go trials (2.5%). Further, switching interacted with frequency, $F(1, 17) = 4.72$; $p < 0.05$, error switch cost was larger for HF words (3.4%) compared to LF words (1.6%) possibly suggesting more complete lexical access for HF words and hence greater interference when processing the relevant (symmetry) dimension.

This experiment aimed at examining the 'residual' switch cost, i.e. the cost that is left after effective preparation. However, whether preparation was indeed effective can only be determined by comparing performance with short preparation to performance with long preparation. Although it has been claimed that a reduction in switch cost cannot be achieved when CSI is manipulated across participants (e.g., Altmann, 2004), in our lab we have obtained strong preparation effects also between participants (Monsell & Mizon, under revision). We ran a short CSI version of the present experiment[3]: 18 participants performed exactly the same paradigm with the only exception that the CSI was 200 instead of 800 ms and the response-cue interval was 1400 ms (to match the present response-stimulus interval). We do not report this experiment in detail here, but comparison of the two experiments showed that switch cost was reliably reduced from 113 ms with a short CSI (200 ms) to 51 ms with a long CSI (800 ms; current experiment), as seen in a reliable switch by CSI (experiment) interaction $F(1, 34) = 15.16$; $p < 0.001$. Error cost reduced from 3% to 2% but this reduction was not reliable $F(1, 34) = 1.84$; $p = 0.18$.

To sum up, behavioural results confirm that our manipulations were successful; reliable effects of switching, frequency and GoNogo were observed. In addition, the comparison with the short CSI study indicates that participants were indeed using the 800 ms to prepare and the major part of the switch cost is residual. (Of course, to be sure that the cost is completely residual one would need several additional long CSIs).

ERPs – semantic task, latency analysis

A principal aim of the experiment was to use ERP to ask which processes are prolonged on a task-switch trial when the participant has had ample time to prepare for the switch. We used the semantic categorization task so that the onset of the word frequency effect around 200-250 ms in the ERP would serve as a marker of lexical access. Hence we could ask: does switching tasks prolong processes before, simultaneous with, or following lexical access?

To answer this question we looked at the effect of a task-switch on the latency of the frequency effect in the ERP, relative to the effect on the overall response time (see LF and

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[3] This experiment is reported in detail in Chapter 3.

HF grand average waveforms and difference waves for switch and repeat in electrodes Pz and POz in Figure 2.4). RT in the semantic task averaged 815 ms on task-repeat trials, and was prolonged by 50 ± 12 ms for the first response following a change of task. The frequency effect in the ERP began around 200 ms after the stimulus onset. The morphology of its evolution appears delayed from the outset on switch trials: an initial maximum in the GFP difference wave (see Figure 2.5) around 275 ms was delayed by a not yet reliable 26 ± 17 ms, t_c (17) = 1.53; $p = 0.14$. A following minimum at round 300 ms was delayed by a reliable 44 ms $\pm$ 13, t_c (17) = 3.32; $p < 0.01$, and the peak of the frequency effect at 500 ms by 62 ± 16 ms, t_c (17) = 3.94; $p < 0.001$. These estimates of delay are sizeable relative to the 50 ms effect of a task switch on response latency. The delay begins to emerge at about 230 ms post-stimulus and is sizeable and reliable around 300 ms. In relation to a mean RT of 815 ms, it indicates that a substantial fraction of the overall effect of a task switch on RT occurs in or prior to lexical access, and hence well prior to response selection, contrary to a number of interpretations of the residual cost reviewed in the Introduction.
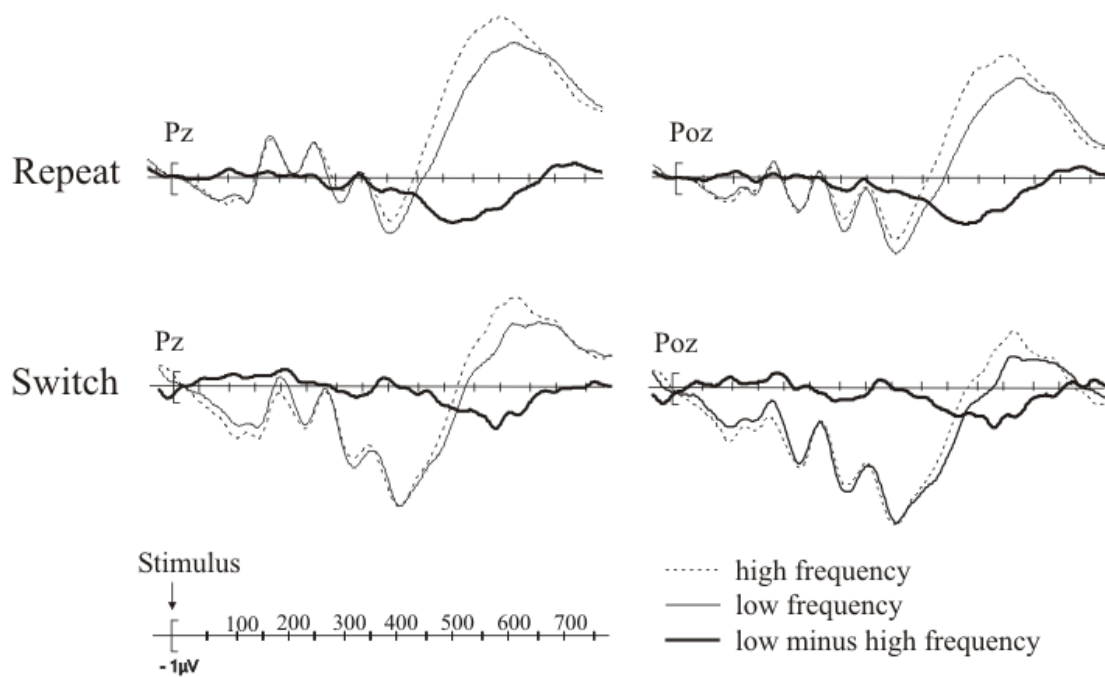
Figure 2.4 *LF and HF waveforms and difference waves for switch and repeat*

ERPs- PCA-based amplitude analyses

A second strategy for determining how early switching affects RT relative to lexical access is to allow the ERP data to suggest underlying processing components (which may overlap)
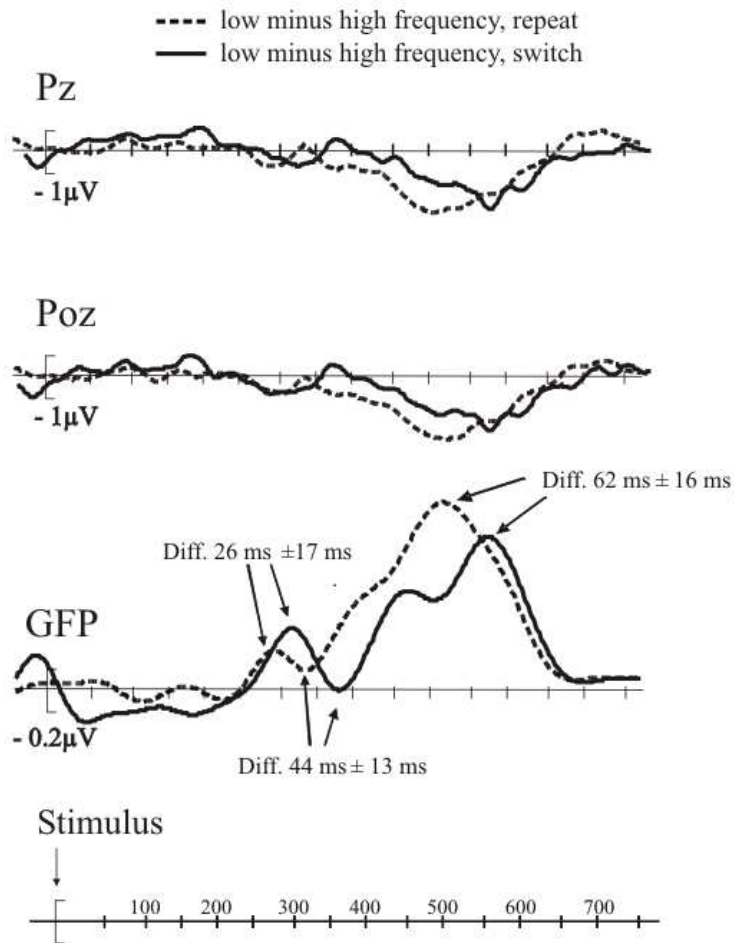
Figure 2.5 *LF and HF difference waves for switch and repeat in Pz, POz and GFP*

and examine each for sensitivity to switching and frequency. Temporal PCAs were run on post-stimulus ERPs of the semantic task, the symmetry task and on ERPs recorded during the CSI.

The PCA analysis identified several components sensitive to frequency (see Figure 2.6 for components and their topographies[4] and Table 2.2 for statistics from ANOVAS of the effects of task, switch/repeat, laterality and region on the amplitude of each component). The earliest of those (component 3: ~195 ms) was also sensitive to a task switch, as was a second (component 4: 250-400 ms) and a third (component 5: 400-600 ms). Ignoring carryover from the pre-stimulus switch-related positivity (component 1) there was also a switch sensitive component (component 2) earlier than the first frequency-sensitive component. We cannot tell how these effects contribute to the RT effect, if they

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[4] All PCA figures show only topographies of significant effects and interactions.
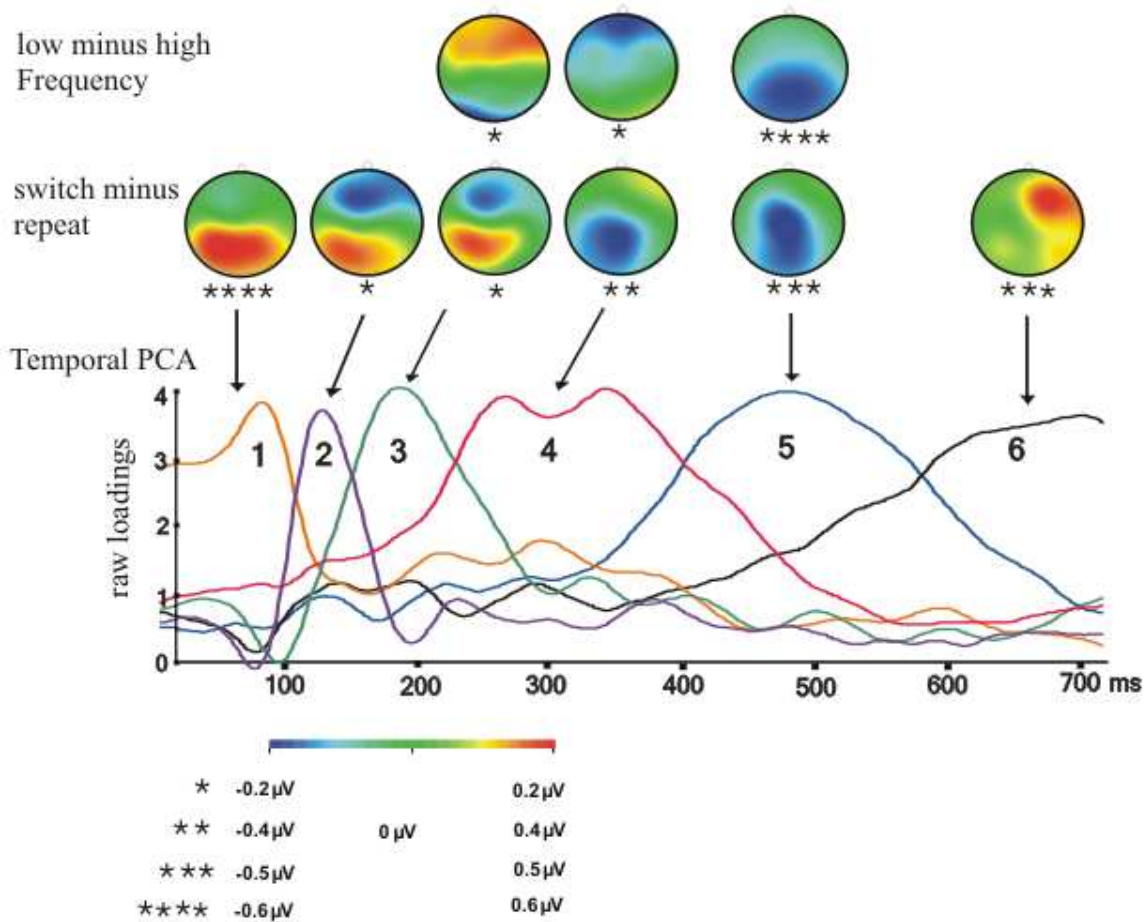
Figure 2.6 *PCA components and their topographies of the semantic task*

do, but they indicate that switching tasks has detectable effects very early in processing, and within or even prior to lexical access. This supports the conclusion suggested by analysis of the latency of the frequency effect. We will consider the implications in the General Discussion. We had also hoped to use the relatively early ERP components typically associated with Go-No-go effects to help localise the switch cost with respect to processing in the symmetry task but we found little sign of such markers in the present data. In a subsequent study[5] we have found that these markers are present in this task, and with these stimuli, when no switching is required. This discovery - that task switching largely eliminates the ERP markers of a Nogo response - is of interest but not germane to our present purpose and we will report and discuss it elsewhere.

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[5] Reported in Chapter 6 of the thesis
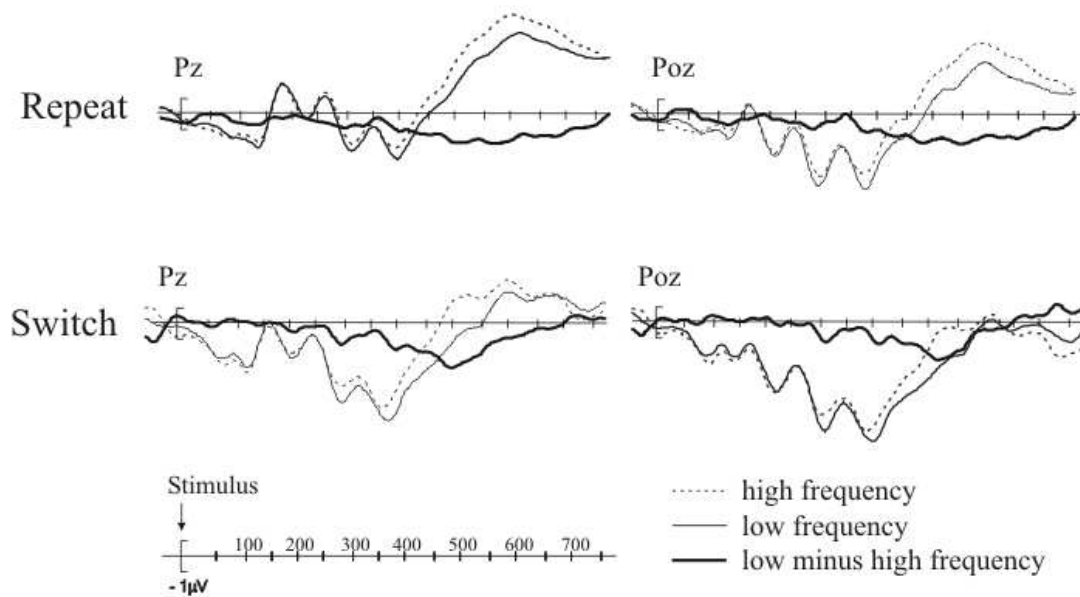
Figure 2.7 *LF and HF waveforms and difference waves in the symmetry task*

Another aim of the experiment was to use the frequency effect on symmetry task trials as an index of the occurrence of lexical access on the symmetry task, when recognition of the word was counterproductive. Sample waveforms from the symmetry task, showing LF and HF ERPs for switch and repeat are shown in Figure 2.7. PCA results are depicted in Figure 2.8 and Table 2.3. On the symmetry task trials, the largest frequency-sensitive component was similar in polarity and topography to that in the semantic categorisation trials (cf Figure 2.6). Crucially, this effect was only present on switch trials. This is consistent with the idea that the residual cost arises in part from greater activation of the processes required for the competing task on switch trials -- whether because such "process activation" merely persists from the previous trial or because a stimulus affording lexical access reactivates that process more when lexical access was deliberately performed on the previous trial. To our knowledge, this is the first ERP evidence of such "inertial" processing of the irrelevant task dimension.

To examine brain activity associated with preparation, sample ERP waveforms for switch and repeat from cue onset until 800 ms post-stimulus are shown in Figure 2.9, PCA components in Figure 2.10 and related ANOVA statistics in Table 2.4. In line with previous investigations in our lab (Lavric et al., 2008; Elchlepp et al., 2011) and others (e.g., Rushworth, Passingham & Nobre, 2005) we found evidence for a brief early positivity for
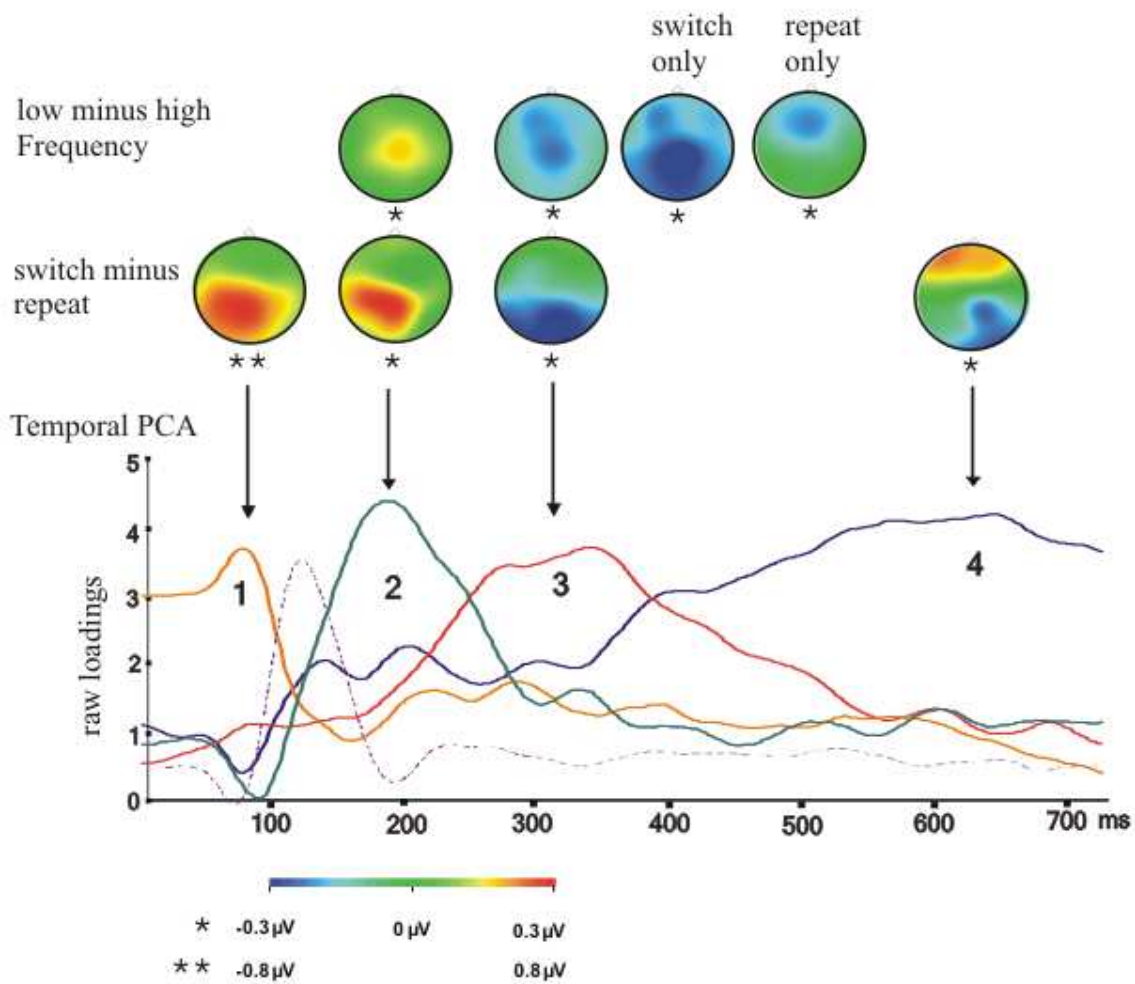
Figure 2.8 *PCA components and their topographies of the symmetry task*
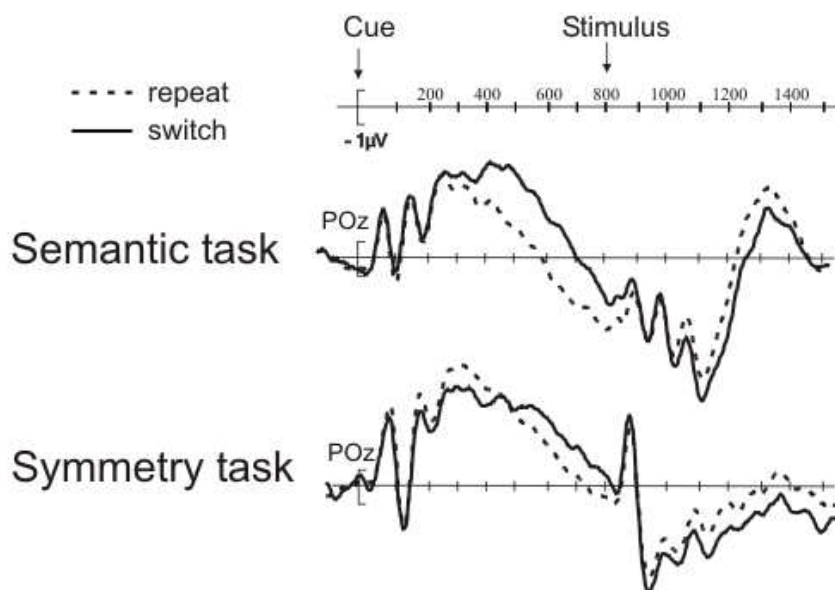
Figure 2.9 *ERP waveforms of the whole trial interval for both tasks*
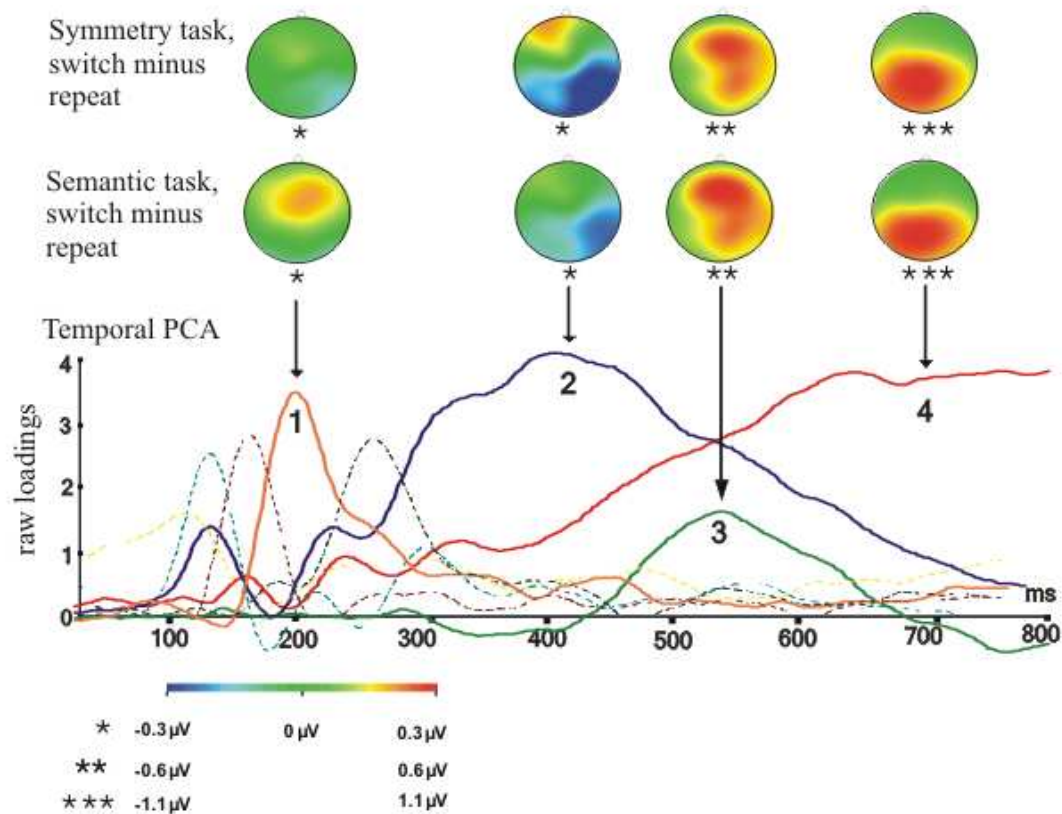
Figure 2.10 *PCA components and their topographies of the cue interval*

switch trials (most easily seen in Figure 2.10), which was, however, only reliable in the semantic task (and the interaction with task was reliable). More importantly, in both tasks we found a highly reliable late posterior switch positivity, captured by the PCA component 4, which explains the largest amount of variance, and also by component 3. This positivity is similar to what we (Lavric et al., 2008; Elchlepp et al., 2011) and others have previously seen in association with effective preparation for a switch for other task pairs. This provides additional reassurance that participants did indeed use the CSI to prepare actively for a switch. This preparatory component is very similar in topography for the two tasks, though with small but reliable differences in laterality between the tasks.

Experiment 2

Experiment 1 showed that switching delays the onset of the frequency effect from about 300 ms on. In the second experiment, we sought to confirm this observation with a different and potentially earlier marker of lexical access, and to avoid the additional complexities of

go/no-go trials by making the symmetry task a binary classification like the lexical task. Lexical access proceeds via activation/selection of a matching form in the lexicon to activation of its meaning. "Lexical identification" and "semantic activation" probably overlap in time and may interact, but to some extent at least, identification precedes semantic activation. Word frequency is likely to impact on both stages (see discussion in Monsell et al., 1989) so we cannot be certain that the ERP effects we are seeing are in "identification" rather than "semantic activation": indeed, we are probably seeing effects at all these levels, and later ones too (integration of meaning with context - N400) as the frequency effect evolves.

In the second experiment we turn to a different ERP index of lexical access: the point at which the evoked response diverges for words and non-words. This is known to be as early, or earlier than, frequency effects. The earliest divergence reported, by Sereno et al. (1998), occurred around 110 ms, with amplitudes becoming more positive for non-words than for words in parietal regions. Most studies have found the effect to emerge from about 200 ms onwards (Dehaene, 1995; Martin-Loeches, Hinojosa, Gomez-Jarabo & Rubia, 1999; Hinojosa, Martin-Loeches , & Rubia, 2001; Hauk, Patterson, Woolams, Watling, Pulvermüller & Rogers, 2006(a); Hauk, Davis, Ford, Pulvermüller & Marslen-Wilson, 2006(b)). Hauk et al. (2006a) report an early (~200ms) anterior positivity for non-words versus words which subsequently turns into a posterior negativity for non-words. Martin-Loeches et al. (1999) refer to posterior amplitudes becoming more positive for words than for non-words around 280 ms as a "recognition potential" for words.

Like word frequency, lexicality should have effects at every stage of lexical access: non-words activate multiple form candidates, but unlike words, no one candidate receives sufficient activation for recognition; non-words may to some extent activate meanings but obviously much less so than words. The leading edge of the divergence between the word and non-word waveforms is likely to reflect the earliest stages of lexical identification. However, if one randomly picked words and non-words, we would be in danger of confounding lexical status with orthographic properties and hence detecting a difference in processing at the pre-lexical encoding stage (at which letter identity and order is represented). Hence, we needed to control bigram frequency. In fact, we not only matched

the words and non-words on bigram frequency, but manipulated bigram frequency orthogonally to lexical status.

Bigram frequency (BF) is strongly correlated with neighbourhood size, which is another variable believed to have effects on early stages of lexical identification when lexical forms partially-matching the stimulus compete (Andrews, 1989, 1992, 1997). We did not attempt the difficult task of disentangling effects of bigram frequency and neighbourhood size. Hence we shall use the term BF-NS to refer to this ambiguous variable when interpreting its effects. If we see an ERP effect of BF-NS preceding lexical status effects, we can be reasonably confident that we are picking up either pre-lexical processing or early stages of lexical identification. And, if that effect too is delayed by a task switch, that would suggest a very early locus for the effect of a task switch. Relatively little is known about the ERP correlate(s) of bigram (or n-gram) frequency. Hauk et al. (2006a), who were particularly interested in very early stages of lexical identification, reported first effects of BF (apparently confounded with neighbourhood frequency) in the ERP at a latency of ~110 ms with more positive amplitudes for low versus high BF items in posterior electrodes. Between this effect of BF and the effect of lexicality at about ~210 ms, they further observed a significant interaction between these two variables (at about ~158 ms). Two ERP studies (Holcomb, Grainger & O'Rourke, 2002 and Braun, Jacobs, Hahne, Ricker, Hofmann, & Hutzler, 2006) have reported orthographic neighbourhood density effects in form of more positive amplitudes for low density items from about 200 ms onwards- a protracted effect maximal over the midline scalp which increased monotonically in posterior channels. We will compare the effect of our BF-NS manipulation to these effects.

Following the logic of Experiment 1, the main point of the second experiment was to examine whether the ERP effect of lexicality, i.e. the point at which the waveforms for words and non-words start to diverge, is delayed on switch compared to repeat trials. To examine a potential delay in even earlier processes we could also compare the onset of BF-NS effects on switch in relation to repeat trials. As in Experiment 1, it was important that the stimulus features and the allocation and spread of spatial attention did not differ for the two tasks. Hence, the symmetry task continued to be a suitable second task. As in Experiment 1, the ERPs from this task will tell us to what extent lexical access appears to

occur "automatically" on the symmetry task trials, whether more so on task-switch trials, as task-set inertia would suggest.

METHOD

Participants

Eighteen right-handed students from the University of Exeter (14 female, 4 male; aged between 18 and 45 (M=21) were given four course credits for participation supplemented by a bonus payment (max £6) calculated on the basis of their performance (see Procedure). Participants gave informed consent following the guidelines set by the University of Exeter School of Psychology ethics committee.

Stimuli and Procedure

On each trial, a 4-7 letter item (word or non-word) was displayed, with some letters coloured in blue and some in red, just as in Experiment 1. One task ('lexical decision task') was to categorise the letter string as a word or non-word by pressing the left or right arrow key, respectively; words and non-words were equiprobable. The "symmetry" task was now to indicate whether the letter colours (blue or red) were distributed symmetrically or asymmetrically using the same left or right arrow keys.

The structure of stimulus sequences, the time-course of individual trials and the cues were the same as in Experiment 1. Of the 2400 items used, half were words and half non-words. Items were selected using the online version of the English Lexicon Project (ELP, Balota et al., 2007)[6] . Half of each subset consisted of high bigram frequency (high-BF, ranging between 2200 – 6900, mean 3387; mean for words 3917; mean for non-words 2859) and half of low bigram frequency items (low-BF, ranging between 1 – 2000, mean 1270; mean for words 1493; mean for non-words 1047; Balota et al., 2007). BF by position "is based on the bigram frequencies that are sensitive to position within words. Position-sensitive bigram counts take into account the letter positions where a bigram occurs. For example, the bigram frequency for DO in DOG counts DO bigrams only when they appear in the first two positions of the word." (Balota et al., 2007, p.450). Both high-BF words and

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[6] The ELP is an American English database which was used because it is – to our knowledge- the only database that contains a measure of bigram frequency by position for a substantial number of words and non-words. We are aware that the BF measure used in this database is relatively crude because it does not take the length of the letter string into account.

non-words had an average orthographic neighbourhood density (computed as the number of words that were different in one letter) of 3; low-BF words and non-words had an average orthographic neighbourhood of 1 (this difference in orthographic neighbourhood size was reliable, $t(2398) = 16.1$; $p < 0.001$). Both high and low-BF words had an average log word frequency of 2.3 (ranging from 0.3 to 5.3; Brysbaert & New, 2009); for further details of item characteristics see Table 2.5. Each item was presented only once in the whole experiment. Items were assigned to task and trial type (switch/repeat) in a pseudo-random fashion for each participant, ensuring that over 6 participants each item occurred once on a switch trial in each task and twice on a repeat trial for each task. Half the items for each combination of BF, lexical status, switch/repeat and task had symmetrical colour patterns randomly assigned to them, half asymmetrical.

Participants were tested on two days; the second testing day being no more than three days after the first. On the first day, the EEG session was preceded by practice comprising four single-task blocks of 24 trials each (two blocks per task), one block of 24 trials of learning cue-task associations, and two blocks of 48 trials of task-cuing trials like the experimental blocks. The electrode cap was then applied and EEG data acquired during 20 blocks, each of 60 experimental trials preceded by a startup trial. On the second testing day EEG data were acquired in a further 20 blocks. In both sessions subjects were instructed to use the cue to prepare for the upcoming task. To encourage effective preparation the same incentive payment scheme was used as in Experiment 1.

EEG and ERPs

The EEG set-up and analysis were the same as in Experiment 1 with the exception that one midline channel used in Experiment 1 was dropped (CPz) and two lateral posterior channels were added (PO5 and PO6). This led to re-grouping of electrodes for the following regions: parietal left, now including CP3, CP5, TP7, P3, P5; parietal middle, now with CP1, CP2, P1, Pz, P2; parietal right with CP4, CP6, TP8, P4, P6; occipital left P7, PO5, PO7, O1; and occipital right P8, PO6, PO8, O2. The remaining regions remained unchanged.

On the first testing day electrode positions of a selection of electrodes (Fp2, F3, Cz, P5, Cp2, O2, T8) were recorded using a CMS ultrasound digitizer (Zebris Medical, Isny,

Germany) so that they could be adjusted on the second day, and electrode positions on the head remained constant across sessions.

ERP latency analysis

In the same way as for frequency in Experiment 1, grand average difference waves for the effect of lexicality were obtained, for switch and repeat trials separately, by subtracting the waveform for words from that of non-words and the global field power of the difference wave was computed. As can be seen in Figure 13A, no local maxima or minima (peaks or troughs) such as those observed in the frequency difference waves in Experiment 1 were evident for use as landmarks for the latency analysis. Instead, the lexicality difference wave showed a monotonic increase with an onset that seemed delayed on switch trials. To estimate the onset of the lexicality effect and compare its latency for switch and repeat trials, we fitted a bilinear function by least squares to an 80 ms (40 time samples, see Figure 2.13B) segment of each difference wave, using the inflection point between the best fitting two linear segments as an estimate of the onset. The second segment was chosen to be long enough to capture an initial portion over 40 ms (20 time samples) where the increase was approximately linear, but short enough that subsequent non-linearities in the difference wave would not affect the estimate of the onset. For repeats, the whole segment fitted was 140 ms to 220 ms following stimulus onset. For switches, the start and end point of the fitted segment was shifted by 40 ms (15 time samples). As in Experiment 1, 'jackknifing' (Miller et al., 1998) was used to compute the standard error over subjects of the difference in onsets between the switch and repeat conditions.

RESULTS AND DISCUSSION

Behavioural results

Mean correct RTs and error rates (excluding the first trial of each block and trials preceded by errors) for all combinations of switch/repeat, task, lexicality and bigram frequency are given in Table 2.6 (see also Figure 2.11). Congruency effects by task and switch-repeat are given in Table 2.7 (see also Figure 2.12). The ANOVAs on mean RTs and error rates included the factors session (first or second), trial type (switch, repeat), task (lexical, symmetry), lexicality (word, non-word), bigram frequency (low, high) and response congruency (congruent, incongruent).

Participants responded faster in the second (857 ms) compared to the first (989 ms) session $F(1, 17) = 43.68$; $p < 0.001$. Responses were slower (955 ms) and error rates higher (7.9%) on switch trials than on repeat trials (891 ms; 5.7%) $F(1, 17) = 34.22$; $p < 0.001$, $F(1, 17) = 22.95$; $p < 0.001$. In the symmetry task responses were slower (990 ms) but more accurate (5.2%) than in the lexical decision task (856 ms; 8.4%) $F(1, 17) = 19.11$; $p < 0.001$, $F(1, 17) = 16.89$; $p < 0.01$. RT switch cost was somewhat greater in the symmetry task (68 ± 14 ms) than in the lexical decision task (59 ± 12 ms), though this difference did not approach statistical significance $p > 0.1$. Error switch cost on the other hand was larger in the lexical task (3.3 ±0.7%) than in the symmetry task (1.1 ± 0.5%), $F(1, 17) = 9.71$; $p < 0.01$. Lexicality interacted with BF for RTs $F(1, 17) = 5.97$; $p < 0.05$, and errors $F(1, 17) = 6.04$; $p < 0.05$; responses to high-BF words were 8 ms faster and more accurate (6.4%) than to
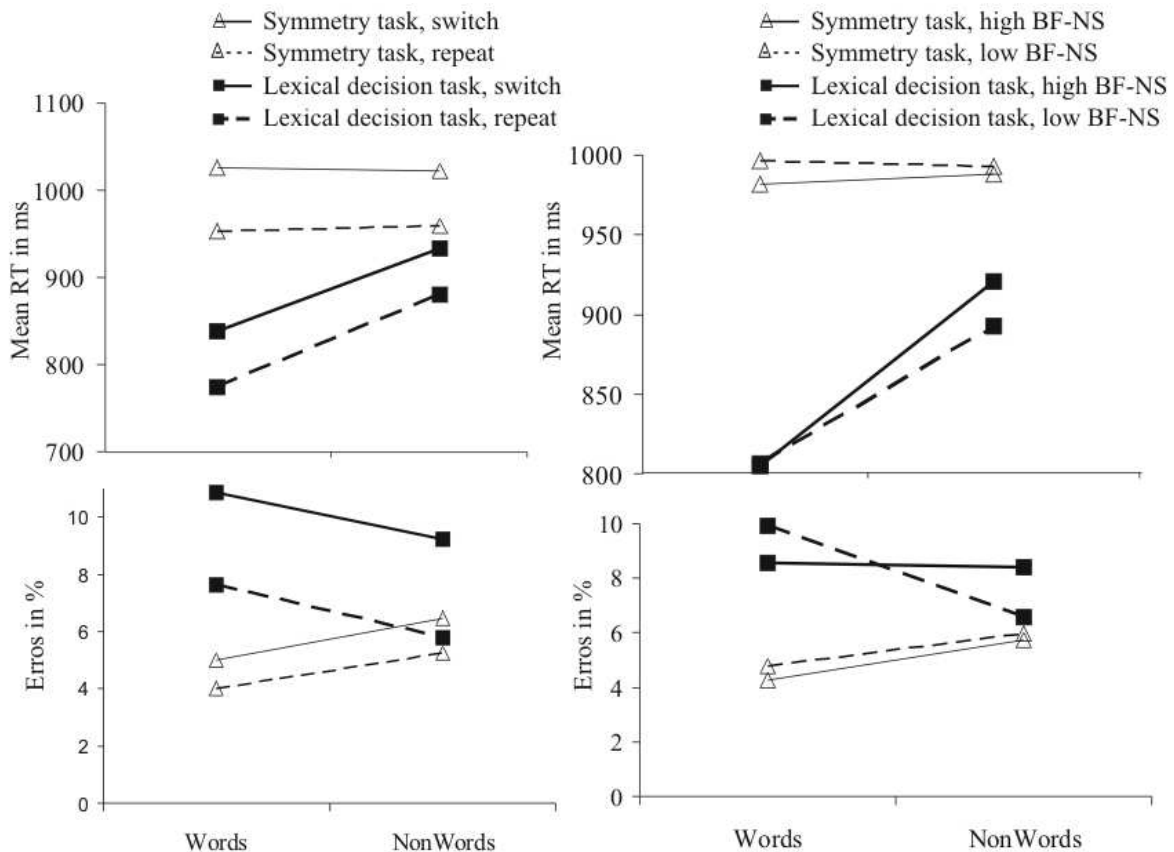
Figure 2.11 *RTs and error rates by lexicality and task for switch-repeat (left) and BF-NS (right)*
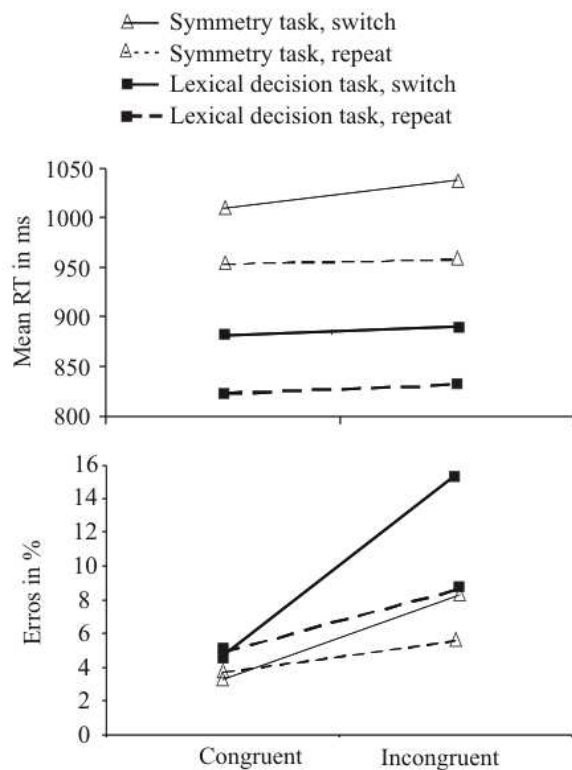
Figure 2.12 *RTs and error rates by switch-repeat, task and congruency*

low-BF words (7.4%), while responses to high-BF non-words were 11 ms slower and more error prone (7.1%) than to low-BF non-words (6.1%). The lexicality by BF interaction was (marginally) reliable for lexical decision task RTs, $F(1, 17) = 4.3$; $p = 0.054$ and errors, $F(1, 17) = 9.78$; $p < 0.01$, but not for the symmetry task F<1 (RTs and errors); the interaction between BF, lexicality and task was not statistically significant for RTs (F<1), but for Errors, $F(1, 17) = 5.45$; $p < 0.05$. Lexicality interacted reliably with task for RT, $F(1, 17) = 69.74$; $p < 0.001$ and errors, $F(1, 17) = 33.33$; $p < 0.001$, with large word-non-word RT differences in the lexical decision task (101 ± 12 ms) and virtually no effect of lexicality in the symmetry task (1 ± 10 ms). More errors occurred for words (9.2%) than for non-words (7.5%) in the lexical task, whilst in the symmetry task slightly more errors were made for non-words (5.9%) than for words (5.4%). RTs of the two tasks also differed in effects of BF $F(1, 17) = 8.99$; $p < 0.01$, with responses being 13 ms faster to low (versus high) BF items in the lexical decision task (an effect entirely due to non-words) and responses being 10ms slower to low (versus high) BF items in the symmetry task.

Responses were (marginally) faster and more accurate for congruent (917 ms, 4.1%) than incongruent (929ms; 9.4%) trials; $F(1, 17) = 4.37$; $p = 0.052$, $F(1, 17) = 42.72$; $p <$ 0.001. For errors, congruency effects (incongruent minus congruent difference) were larger for switch (7.8%) than for repeat (2.8%) trials, $F(1, 17) = 28.96$; $p < 0.001$ and larger in the lexical (7.2%) than the symmetry (3.4%) task, $F(1, 17) = 12.58$; $p < 0.01$. The difference in congruency effects between switches and repeats was greater in the lexical task (switch 10.7%, repeat 3.7%) than in the symmetry task (switch 4.9%, repeat 1.9%) (switch by task by congruency interaction, $F(1, 17) = 8.18$; $p < 0.05$).

To sum up, behavioural performance was typical of both task switching and lexical decision with slower responses (and higher error rates) on switch compared to repeat trials and a substantial effect of lexicality on RTs and errors in the lexical decision task but not in the symmetry task. In the lexical decision task, lexicality interacted with BF-NS with longer RTs and more errors for low BF than for high BF words, and the opposite pattern — shorter RTs and fewer errors for low BF than for high BF non-words. Response congruency effects indicated greater activation of responses via the irrelevant task-set on switch than on repeat trials.

Lexical decision task: ERP latency analyses

To assess a possible delay in the onset of lexical identification due to a task switch, we compared the onset of the lexicality effect (word versus non-word) in the ERP for switch versus repeat trials (See Figure 2.13 for GFP difference wave of the segment used for the function fitting (2.13B), the GFP difference wave of the whole post-stimulus interval (2.13A). When subjects repeated the lexical decision task, the (GFP) non-word-word difference wave started rising at ~182 ms. Switching to lexical decision delayed the onset of this lexicality effect by 59 ± 13 ms, $t_c (17) = 2.20$; p< 0.05, a delay whose magnitude is remarkably similar to the RT switch cost in the lexical decision task (59 ± 12 ms). The earliness of this offset (~200 ms following stimulus onset) strongly supports the notion that a substantial part of the residual switch cost has an early locus.

We had also hoped to look for a similar delay in the onset of the effect of the BF-NS variable. Such an onset is visible at about 220 ms on the task-repeat trials (Figure 2.14, top
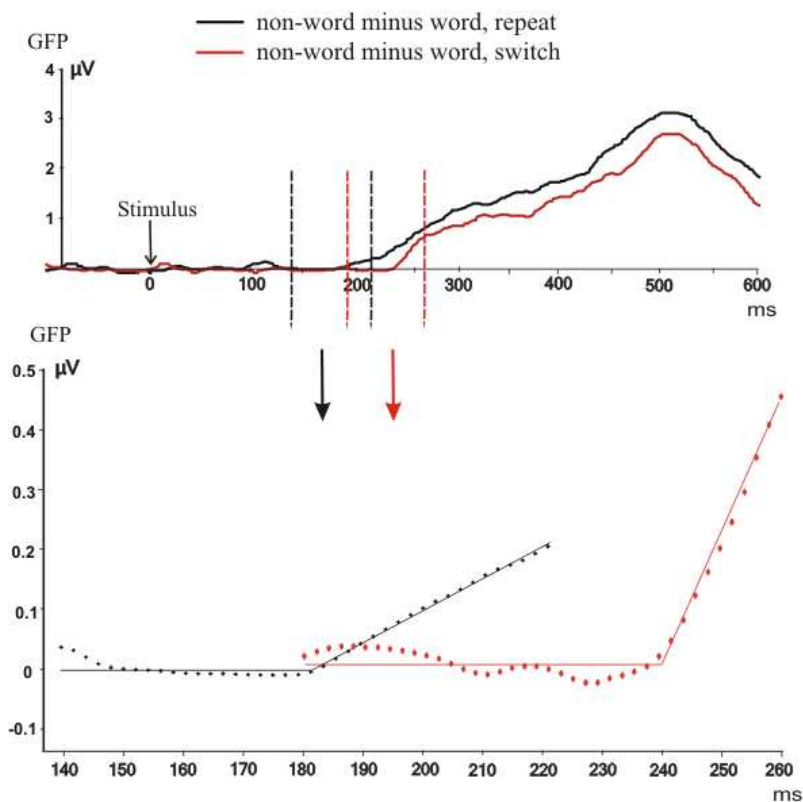
Figure 2.13 *GFP difference wave of the whole post-stimulus interval (top) and the segment used for function fitting (bottom)*
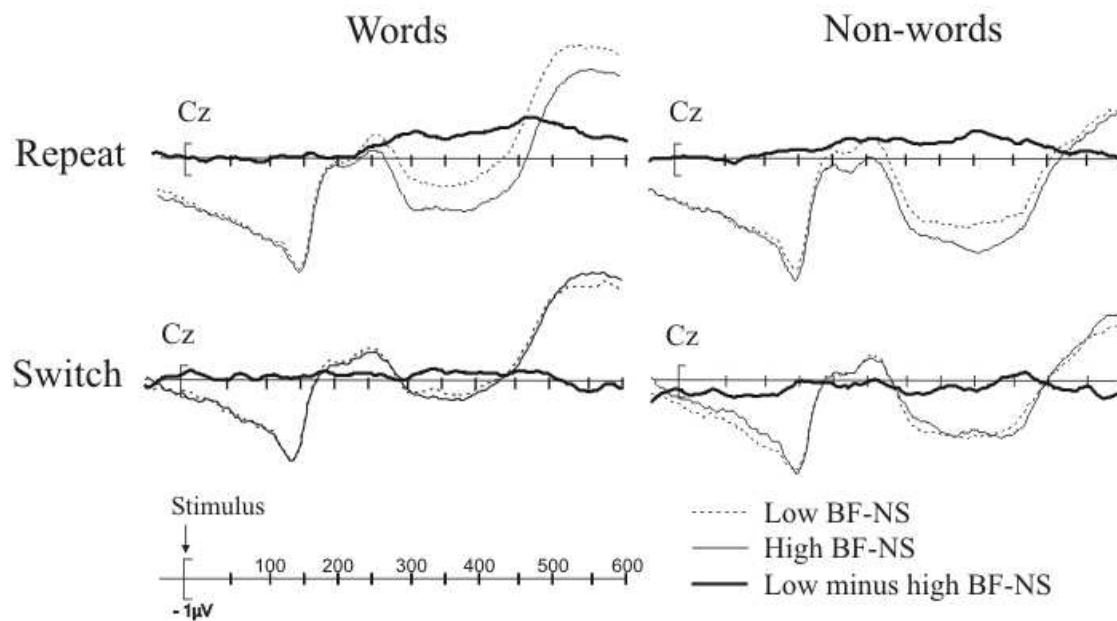
Figure 2.14 *ERP waveforms and difference waves for low and high BF-NS, separate for switch and repeat words and non-word trials*

panels). But the effect was largely absent on the task-switch trials (bottom panels) — an observation to which we return below — so a similar latency analysis could not be performed for the onset of an effect of BF-NS in the ERP.

ERPs- PCA-based amplitude analyses

Sample ERP waveforms for switch- and repeat lexical task trials are shown separately for words and non-words in Figure 2.15. PCA components for lexical decision task are shown in Figure 2.16 and relevant ANOVA statistics in Table 2.8). Switching affected ERP
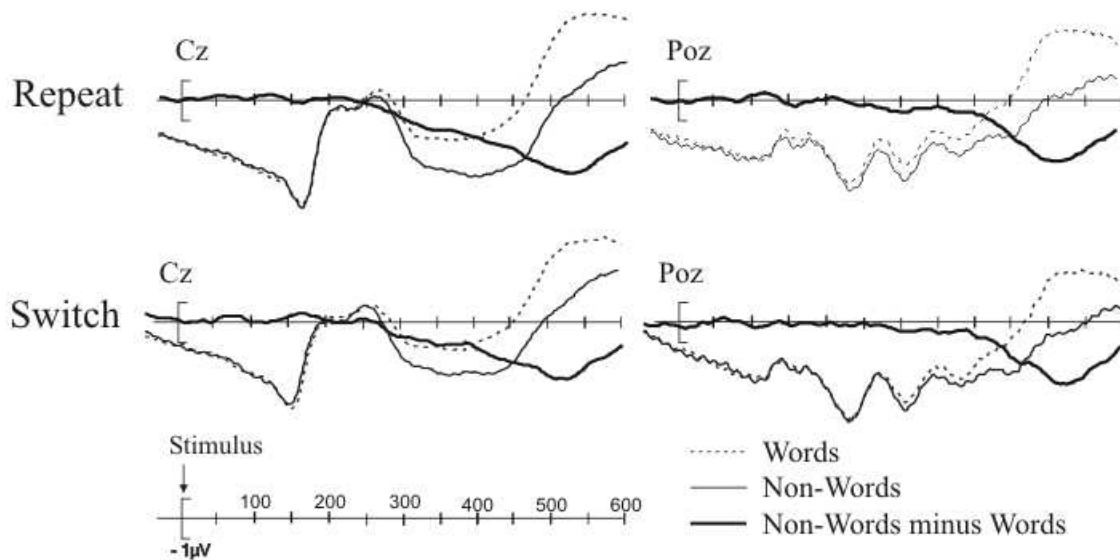
Figure 2.15 *ERP waveforms and difference waves for words and non-words, separate for switch and repeat*

amplitudes throughout the entire post-stimulus interval for both tasks. The effect on the first component can be discounted as due to carry over of the preparation-related switch positivity. Following that, several PCA components captured switch-induced negativities similar to those reported previously (e.g., Nicholson, Karayanidis, Poboka, Heathcote & Mitchie, 2005; Lavric et al., 2008; Elchlepp et al., 2011). Differences between words and non-words emerged in the ERP from ~150 ms onwards and lasted until the end of the interval. At the early stages, lexicality differences (more positive amplitudes for non-words) were larger for low than high BF items (an interaction considered in the General Discussion). The main effect of lexicality became reliable in a PCA component peaking at
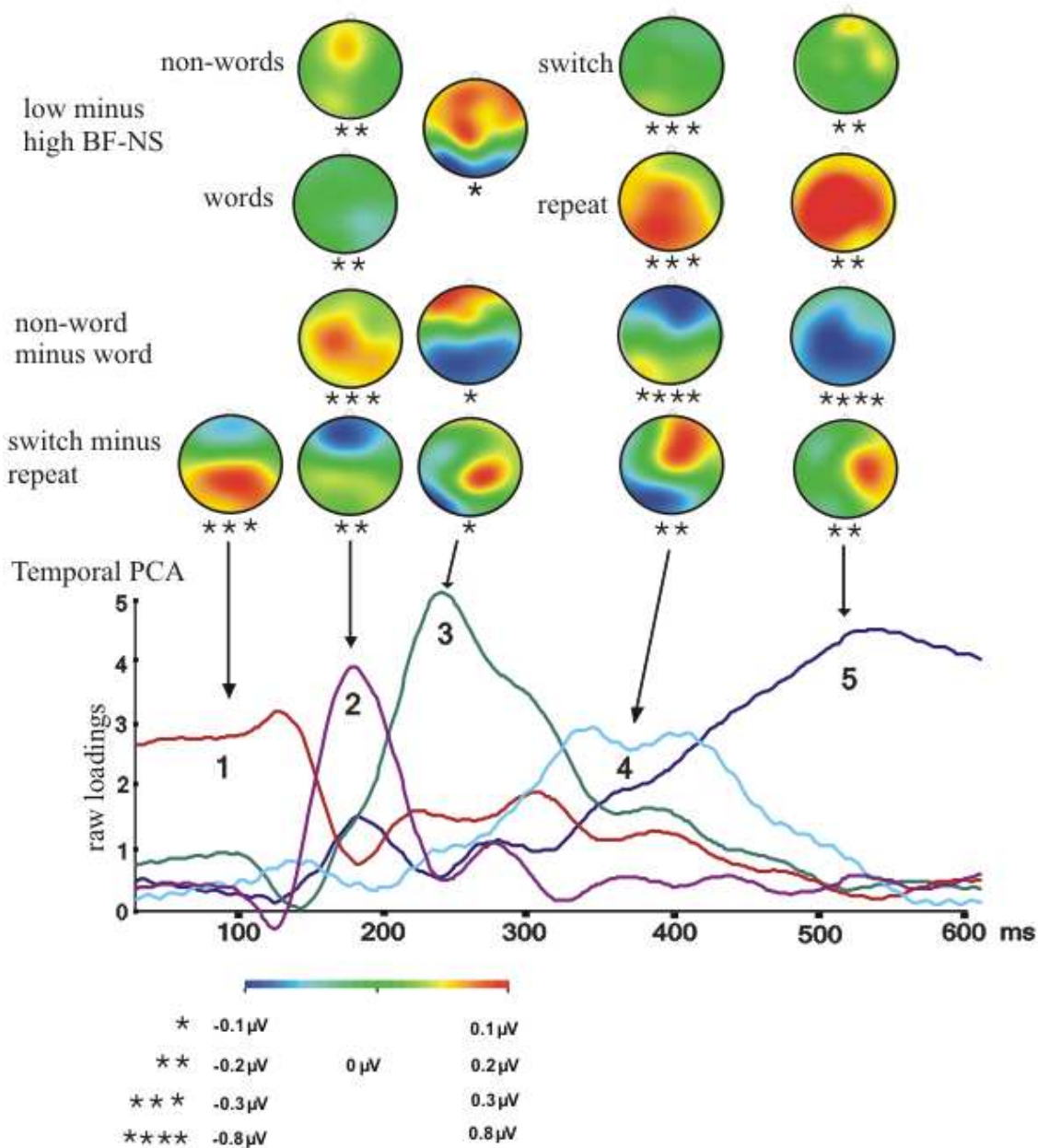
Figure 2.16 *PCA components and their topographies of the lexical decision task*

~160-170 ms, which is in line with the estimated onset of lexicality effects (on repeat trials) in the latency analysis presented above. At ~220 ms, circumscribed effects of BF-NS were present for all trial types. The timing, polarity and topography of our BF-NS effects is very similar to previously documented ERP orthographic neighbourhood effects (e.g., Holcomb et al., 2002; Braun et al., 2006) so it is plausible that the effect reflects neighbourhood size. From about 300 ms onwards switching interacted with BF-NS; low versus high BF differences were large on repeat trials yet nearly absent on switch trials (as noted above).

Thus, switching affected lexical decision ERPs in two ways: it delayed lexical processing as early as ~200 ms and it almost abolished the large effects of BF/orthographic neighbourhood density seen on repeat trials from ~ 300 ms onwards.

Symmetry task. ERPs (Figure 2.17 and Table 2.9) were affected by lexicality throughout the whole interval and the time course, polarity and topography of this effect were very similar to those in the lexical decision task. While lexical properties of the stimulus are evidently reflected in processing on both, switch and repeat trials, word- non-word differences were larger on switch trials, particularly early in the interval. Experiment 1 found only a later switch related modulation of the effect of lexical variable in the symmetry task. This could be due to wordness interfering earlier than word frequency effects; but it could also be due to a greater sensitivity of the analysis in Experiment 2 since trial numbers were twice as large here due to having two sessions. (Early ERP effects are often noisier and hence more variable than later ones. This was in fact one reason to run Experiment 2 in two sessions.) The effect of BF-NS was also greater/more widespread on switch trials. This further supports the notion that the irrelevant stimulus attribute is processed to a greater extent on switch trials and subsequent competition between responses activated by relevant and irrelevant task features contributes to the residual cost.

PCA analyses of pre-stimulus ERPs during the cue interval (Figure 2.18 and Table 2.10) confirmed previous findings: an early positivity for switch was found for the lexical decision task and both tasks showed a large late posterior positivity for switch.
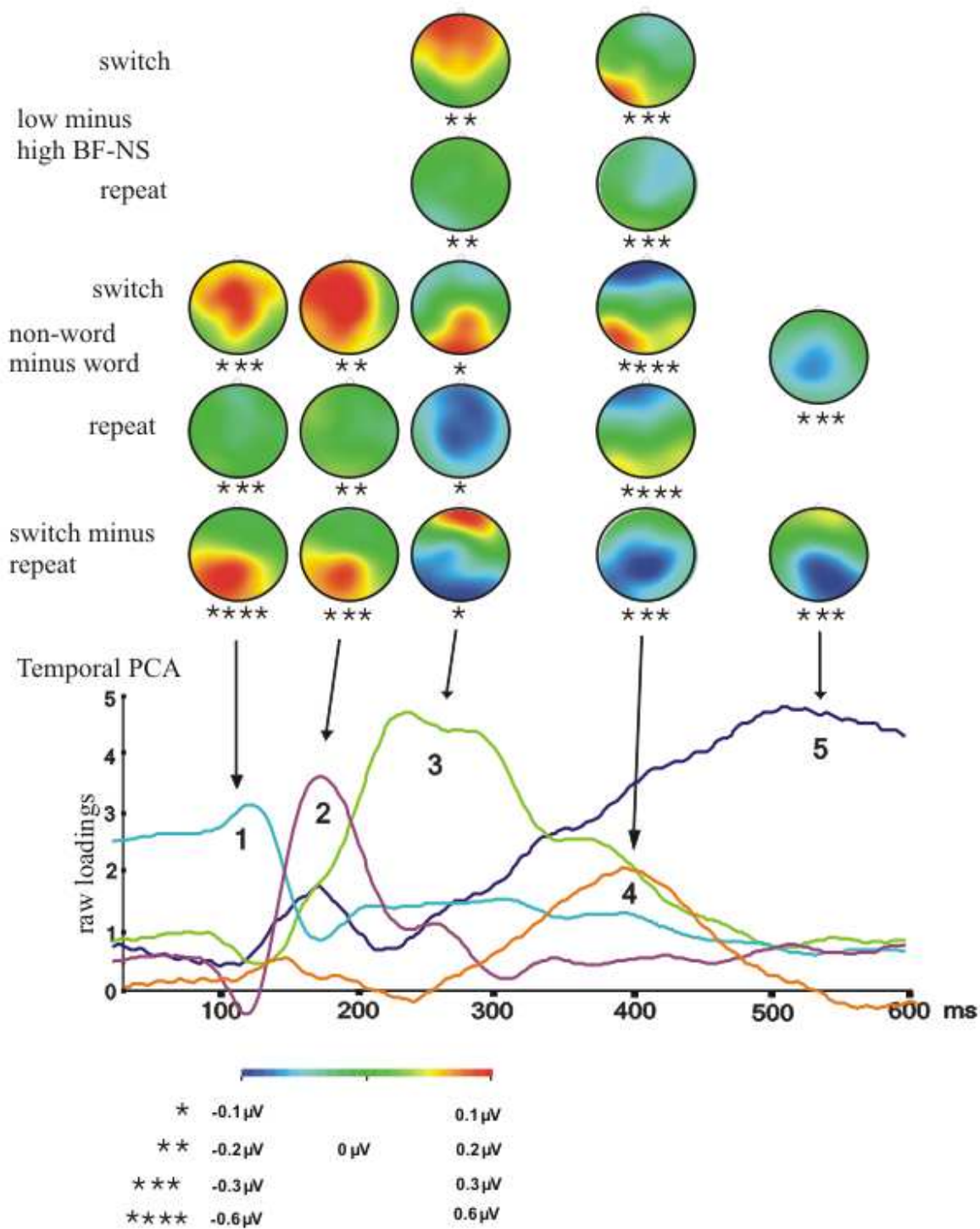
Figure 2.17 *PCA components and their topographies of the symmetry task*
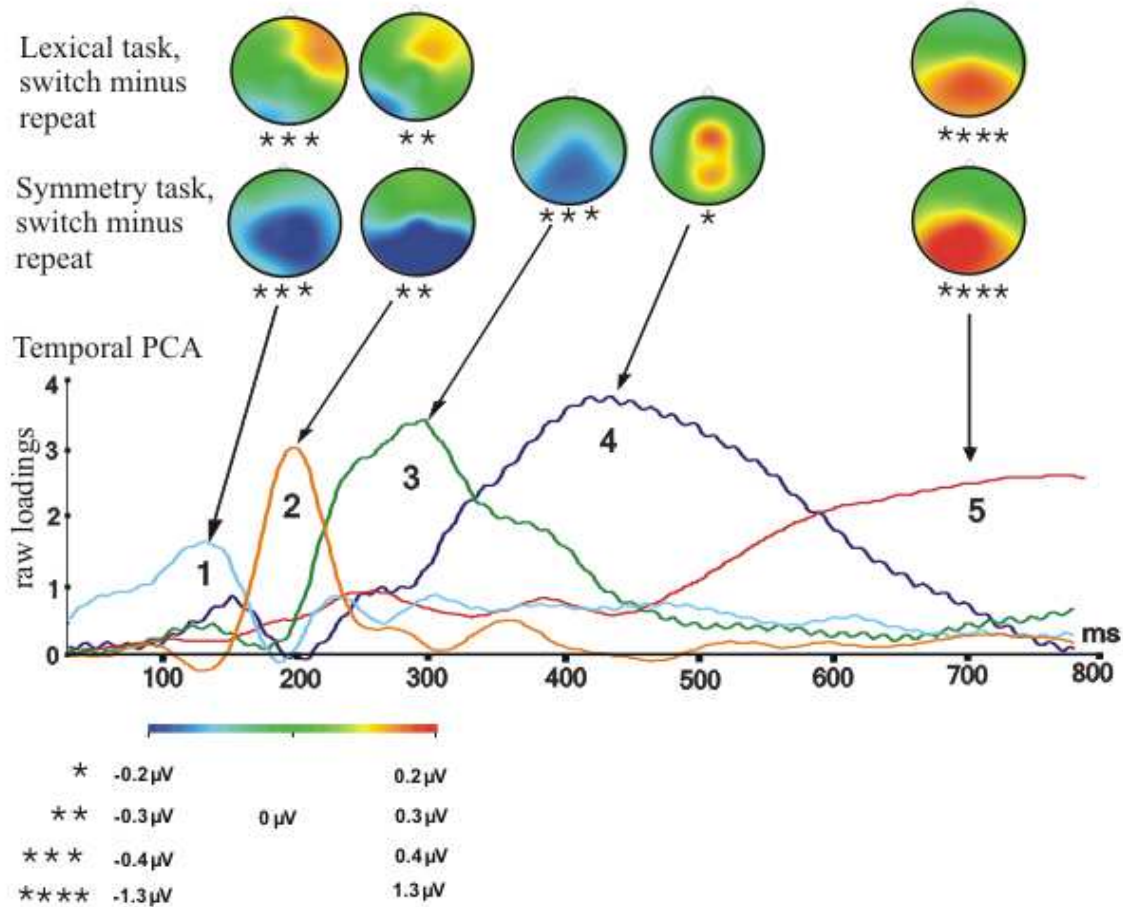
Figure 2.18 *PCA components and their topographies from the cue interval*

General Discussion

In two experiments we cued participants to perform a lexical or non-lexical task on a letter string, with 800 ms to prepare following the cue. As usual RT was prolonged on a switch trial. We used ERP latencies to investigate the locus of this switch cost within the latent interval for the lexical task. In Experiment 1, participants categorised words as living/ non-living and the onset of the word frequency effect in the ERP was used as a marker of lexical access. ERP waveforms for low and high frequency words started to diverge at ~ 250 ms and switching reliably delayed this onset by a substantial amount relative to the RT switch cost as early as ~300ms. Experiment 2 confirmed and extended this finding using a different and earlier marker of the onset of lexical access: the effect of lexicality (word versus non-words) The onset of the lexicality effect at ~200 ms was delayed on switch trials by about 60 ms, again an amount similar to the switch cost.

In Experiment 2 we also orthogonally manipulated bigram frequency and orthographic neighbourhood size, and this had behavioural effects consistent with effects of the latter. There were suggestions of very early delays in the emergence of effects of BF-NS in the ERPs on task-repeat trials but these were not reliable. However, the effects of this variable on ERP amplitude were modulated by a task-switch in a qualitatively interesting way: on repeat trials BF effects were large and spread over wide areas of the scalp, on switch trials the effects were small and circumscribed.

Finally, the effects of lexical properties on ERPs during performance on the symmetry task indicated that unwanted but "automatic" lexical access occurred on the symmetry task trials, but more so immediately following a switch from the lexical to the symmetry task -- clear evidence for "task-set inertia".

Implications for theories of the residual task-switch cost
An effect of task switching on processing so early – between 200 and 300 ms post-stimulus — and the sizes of the average delay at this early stage — 42 ms in Experiment 1, 59 ms in Experiment 2, relative to the RT switch cost (~ 60ms in both experiments) — together suggest that a switch of task, after preparation, prolongs processing early within the latent interval – i.e., in early lexical or pre-lexical processing, rather than the later response-selection process How does this fit in with the theories of the residual cost we reviewed in the Introduction?

Exogenously triggered completion of reconfiguration. Rogers and Monsell (1995) suggested a second stage of TSR triggered by the stimulus, and Rubinstein et al. (2001) proposed that this stage involved retrieval of S-R rules into working memory. This theory is certainly compatible with an early locus of the residual switch cost, as the S-R rules must presumably be retrieved prior to response selection. Rogers and Monsell's broader suggestion is also compatible with other possibilities, such as the completion of reorientation of attention to the relevant stimulus attributes requiring exogenous activation by the stimulus.

Task-set inertia. The idea that activation and or inhibition of task-set from the previous trial carry over and delay processing on switch trials receives strong support from ERP

amplitudes early in processing on the symmetry task trials. These indicated that lexical access was clearly happening even when unwanted, and more so on switch trials. This is consistent with Yeung et al.'s (2006) finding that switch cost correlated with fMRI activations in brain regions associated with the irrelevant task. We believe it provides the first neurophysiological evidence for task-set inertia in a paradigm using trial-to-trial switching with a preparation interval sufficiently long for successful preparation. The early locus of the effect of a prepared switch on the lexical task thus suggests that the principal source of extra interference on task-switch trials is not persistence of the S-R mappings from the previous trial (which should specifically prolong response-selection), but persisting allocation of attention (or processing resources) to the irrelevant stimulus attribute -- *attentional* inertia.

Associative reactivation of task-set. As conceived of by Waszak et al (2003, 2004, 2005) the effect of extra associative reactivation of a task-set on a switch trial is to prolong response-selection. That does not seem compatible with an early locus of the effect of a switch. But the early locus is compatible with the idea that what the stimulus reactivates is a task-specific attentional orientation.

Response-contingent reconfiguration. In Meiran's (2000; Meiran et al., 2008) account of the residual cost, while attention may be redirected to a different dimension during preparation for a task change, a response has to be generated at least once to change the meaning of the response set (S-R weighting) to optimise performance. In contrast, our results suggest pre-response-selection processing is slowed – possibly by attentional inertia– even after preparation. Schuch and Koch (2003) also emphasise response-selection, proposing that even after full preparation a bivalent stimulus elicits conflict and the residual switch cost reflects task-set suppression applied during response selection to resolve the conflict. But our results suggest an earlier locus of the major part of the residual switch cost.

In summary, our conclusion is that the ERP data from the lexical tasks demonstrate that, after preparation the effect of a task-switch is mainly to prolong the duration of processes well before response selection. For the lexical tasks that we used, these processes could be pre-lexical encoding or relatively early stages of lexical access. Either is compatible with the idea of "attentional inertia": a difficulty reorienting attention to

orthographic attributes, or a difficulty reactivating the lexical pathway, until the lexical task has been performed at least once. The ERP data from the symmetry task also support a general task-set inertia account: lexical properties of the stimulus were processed more deeply on switch trials than on repeat trials.

Possible limitations

Our experiments were intended to investigate the residual cost, i.e. the cost that is left after successful preparation. But it would be rash to claim that the active part of reconfiguration was completely accomplished before the stimulus on all trials. One of our previous investigations (Lavric et al., 2008) looked at preparation effects in trials with fast versus slow responses and found a switch positivity in the stimulus interval of slow-response trials similar to the one found on short CSI trials where there is no opportunity to reconfigure before the stimulus, suggesting that, even with an interval sufficient for preparation, on a proportion of trials reconfiguration takes place after stimulus onset (cf De Jong, 2000, Nieuwenhuis & Monsell, 2002). Trial numbers in the present experiments did not allow us to perform separate analyses for fast and slow trials, so we cannot rule out the possibility that post-stimulus reconfiguration on a proportion of trials contributed to the processing delays measured on switch trials. We doubt, however, that delayed preparation is the sole or major source of the ERP latency effects observed for the following reasons: the length of the CSI (800 ms) was chosen to be greater than the CSI at which switch cost becomes asymptotic in most studies; the residual cost in the lexical tasks (~60 ms) is of the same order as residual costs in other studies (e.g., Lavric et al., 2008; Nicholson et al., 2005); switch cost was reduced by about half in the 800 ms CSI experiment (Experiment 1) compared to the 200 ms CSI version, suggesting successful preparation); we found a highly reliable preparation-related positivity in ERPs of both studies. These points suggest that participants used the 800 ms CSI on most of the trials to prepare and the switch cost we investigated was largely residual.

Another possible limitation is that, although we chose the tasks between which participants switched to require the same distribution of spatial attention, we cannot be certain that is was identical for the lexical and symmetry tasks. We can only note that if substantially different distributions of attention were being achieved for the two tasks, we might expect participants to have been more successful in suppressing lexical access on

symmetry trials (cf Besner et al.'s modulation of Stroop interference by spatial zooming). It will be desirable to look for similar evidence with other pairs of tasks where reorientation of spatial attention is an even less likely source of processing delays.

Implications of the bigram frequency/neighbourhood size effects
We expected the effects of the BF-NS variable to emerge early in the ERP, possibly even preceding the effect of lexicality, as bigram frequency, per se, is likely to influence pre-lexical processing of orthography. And indeed ERP waveforms for low versus high BF non-words started to diverge at ~100 ms, and for words at ~200 ms (see Fig. 13). But these early differences were not reliable, nor were they reliably modulated by switching. Local differences became reliable at ~200ms, generalizing across the whole scalp from about ~300 ms onwards but only for task-repeat trials. This interaction with switching is both unexpected and intriguing. Given the similarity of the effect of BF-NS in timing and topography to effects of orthographic neighbourhood previously reported (e.g., Holcomb et al., 2002; Braun et al., 2006), it is quite likely that what we were seeing was in fact the effect of this variable. BF-NS also interacted with lexicality, such that high BF words were recognized faster than low BF words while for non-words the opposite was true.

The behavioural interaction between BF and lexicality for RT might be interpretable as follows. Lexical decision is partially driven by global activation of the lexicon which provides a measure of wordlikeness (Grainger & Jacobs, 1996): high wordlikeness permits a rapid word decision without precise identification; low wordlikeness permits a rapid non-word decision. A high BF word activates more neighbours than a low BF word, all other things being equal, and hence the "word" decision is facilitated. A low BF word activates fewer neighbours than a word, and hence the "non-word" decision is facilitated. In the ERPs, BF-NS interacted with switching and task so that the BF-NS effect was substantially reduced immediately after a switch to the lexical task. After a switch to the symmetry task, on the other hand, the effect was enhanced compared to symmetry task repeats. An obvious assumption would be that this simply reflects persisting lexical activity. Our finding that lexicality effects were not reduced when switching to lexical decision (compared to repeating this task), instead they were delayed, does not seem to fit this interpretation. Holcomb et al. (2002) suggested that monitoring the global activation of the lexicon is a top-down process that can be exerted when beneficial to performance. They based this on

their finding that neighbourhood effects in the ERP were much larger in a lexical decision task (when such monitoring improves performance as described above) compared to a semantic decision task (when the individual item has to be found in the lexicon and global activation is not helpful). With regards to our data this could mean that attentional biasing and monitoring is applied more effectively when the previous trial required it, i.e., on lexical task repeat trials. It might need one trial of performing the lexical task to be fully instantiated. Once employed it seems to persist into the next trial, as observed on trials when one has just switched away from the lexical task.

Implications for the automaticity of word-reading

It used to be a commonplace claim that after extensive practice at reading, recognition of an attentively fixated word becomes "automatic" (e.g., Brown, Gore, & Carr, 2002; La Berge & Samuels, 1974; Posner & Synder, 1975) -- implying involuntariness, lack of attentional resource demand, or both, As reviewed in the introduction, a more nuanced view has developed in recent years, recognising first the importance of the distribution of spatial attention (Besner et al., 1997) and secondly the results from PRP studies of the resources required for lexical tasks such as reading aloud (Reynolds & Besner, 2006; O'Malley, Reynolds, Stolz & Besner, 2008) and lexical decision (Lien et al., 2008). For naming, Besner et al. conclude that sublexical phonological processing (the assembly route in dual route models) requires some form of attention whilst early orthographic processing of features and letters as well as early lexical processing (activation of the orthographic input lexicon), is automatic. Paulitzki, Risko, O'Malley, Stolz & Besner (2009) report experiments in which participants were cued to read the word or to make an upper/lower case judgement. The auditory cue preceded the stimulus by 0 or 750 ms. They reasoned that if lexical processing is automatic then it should not be affected by encoding the task cue. Their Experiment 1 suggested that some pre-lexical processing seemed to be possible in parallel with encoding the cue. However, the factor of task sequence (switch, repeat) was not included in their analysis. This is problematic because the task-switching literature provides evidence that on repeat trials the task set is already reasonably well established, which means subjects can perform well on the task even when the CSI is zero. Their Experiment 2 did look at the effect of previous trial but only found a switch by CSI interaction (i.e., a RISC effect) and no three-way interaction of those factors with their lexical variable word frequency.

Lien et al. (2008) combined ERPs with the PRP procedure to look at delays in lexical processing when lexical decision was the second of the two tasks. When the SOA was short, the effect of word frequency on N400 amplitude (indexing semantic activation) was strongly attenuated and its effect on P3 (argued to index lexical activation) was nearly abolished. This led the authors to conclude that neither lexical nor semantic activation can proceed very far without central attention. In contrast to the PRP situation, where the latent S-R intervals for two tasks overlap, our participants had 1600 ms to recover from executing the previous task, and 800 ms advance foreknowledge of having to perform the lexical task. But it is tempting to see our findings as on a continuum with theirs, as we found that the cognitive demands of switching away from a different task postponed or prolonged early stages of lexical access. This suggests that lexical access is not automatic in the sense of proceeding invariantly, even with appropriate allocation of spatial attention. Moreover, although the ERPs suggest that lexical access occurred involuntarily on symmetry task trials, they also suggest that lexical activation was greater on a switch trial than after the task-set was more securely established, evidence that lexical access is to some degree dependent on the allocation of attention or cognitive resources, and hence influenced by inertia in that allocation.

Appendix Chapter 2: Data tables

		Semantic task				Symmetry task			
		Frequency		Symmetry		Frequency		Symmetry	
		High	Low	Asym	Sym	High	Low	Asym (Go)	Sym (Nogo)
Switch	Mean RTs in ms (% errors)	848 (4.1)	883 (6.2)	854 (5.2)	885 (5.3)	946 (6)	956 (5.3)	951 (3.6)	-- (9.2)
Repeat	Mean RTs in ms (% errors)	803 (3.5)	828 (4.5)	813 (4.1)	819 (3.6)	896 (2.9)	901 (3.8)	899 (1.2)	-- (6.6)
Switch cost	Mean RTs in ms (% errors)	45 (0.6)	55 (1.7)	42 (1.1)	65 (1.7)	50 (3)	54 (1.6)	52 (2.4)	-- (2.7)

Table 2.1 *RTs, error rates and switch costs of experiment 1*

PCA Compo-Nent	Variance accounted for	Peaking at/ High loadings between	Significant effects in ANOVA	df	F	p
1	12.4%	85 ms	switch switch x region switch x region x lat	1,17 3,51 6,102	7.93 14.88 11.1	< 0.05 < 0.01 < 0.01
2	5.4%	130 ms	switch x region	3,51	6.45	< 0.05
3	11.7%	195 ms	switch x region switch x region x lat freq x region switch x freq x region	3,51 6,102 1,17 3,51	9.62 4.16 8.85 2.99	< 0.01 < 0.01 < 0.01 0.087
4	23.8%	250 – 400 ms	switch switch x region switch x lat switch x region x lat freq x region	1,17 3,51 2,34 6,102 3,51	6.45 26.81 15.94 9.35 6.03	< 0.05 < 0.001 < 0.001 < 0.001 < 0.05
5	22.9%	400 - 600 ms	switch switch x region switch x lat switch x region x lat freq freq x region freq x lat freq x region x lat	1,17 3,51 2,34 6,102 1,17 3,51 2,34 6,102	12.53 5.16 27.15 8.04 22.82 18.77 12.81 18.56	< 0.01 < 0.05 < 0.001 < 0.001 < 0.001 < 0.001 < 0.001 < 0.001
6	17.7%	600 – 750 ms	switch switch x lat switch x region x lat	1,17 2,34 6,102	5.88 5.05 3.59	< 0.05 < 0.05 < 0.01

Table 2.2 *Statistics of PCA components of post-stimulus ERPs from the semantic task, (Exp.1)*

PCA Compo-Nent	Variance accounted for	Peaking at/ High loadings between	Significant effects in ANOVA	df	F	p
1	12.8%	85 ms	switch switch x region switch x lat switch x region x lat	1,17 3,51 2,34 6,102	14.71 8.61 6.13 9.73	< 0.01 < 0.01 < 0.01 < 0.001
2	15.5%	200 ms	switch x lat switch x region x lat freq x lat	2,34 6,102 2,34	4.62 3.52 3.55	< 0.05 < 0.05 < 0.05
3	20%	250 – 400 ms	switch frequency switch x region switch x region x lat switch x freq x reg x lat switch only: frequency freq x region x lat	1,17 1,17 3,51 6,102 6,102 1,17 6,102	5.42 3.98 7.71 2.55 3.14 4.19 3.12	< 0.05 < 0.05 < 0.01 < 0.05 < 0.05 0.056 < 0.05
4	38.4%	450- 700 ms	switch x region	3,51	9.79	< 0.01

Table 2.3 *Statistics of PCA components of post-stimulus ERPs from the symmetry task, (Exp.1)*

PCA Compo-Nent	Variance accounted for	Peaking at/ High loadings between	Significant effects in ANOVA	df	F	p
1	6.5%	190 ms	switch x task	1,17	6.15	< 0.05
			switch x region	3,51	6.65	< 0.05
			switch x task x lat	2,34	4.05	< 0.05
			switch x task x reg x lat	6,102	3.1	< 0.05
			semantic task:			
			switch	1,17	10.27	< 0.01
			switch x lat	2,34	3.83	< 0.05
2	35%	310- 500 ms	switch x region	3,51	9.94	< 0.01
			switch x lat	2,34	6.3	< 0.01
			switch x region x lat	6,102	2.7	< 0.05
			switch x task x region	6,102	5.22	< 0.05
			symmetry task:			
			switch x region	3,51	10.69	< 0.01
			switch x lat	2,34	7.6	< 0.01
			switch x region x lat	6,102	2.83	< 0.05
3	2.6%	530 ms	switch	1,17	5.11	< 0.05
			switch x task x lat	2,34	3.41	< 0.05
4	37%	450 - 800 ms	switch	1,17	29.34	< 0.01
			switch x region	3,51	24.85	< 0.001
			switch x lat	2,34	9.78	< 0.01
			switch x region x lat	6,102	22.45	< 0.001
			switch x task x lat	2,34	3.61	< 0.05

Table 2.4 *Statistics of PCA components from ERPs of the cue interval, (Exp.1)*

	Words- Low	Words- High	NonWords-Low	NonWords-High
4 letters	28	26	25	19
5 letters	115	109	109	102
6 letters	189	185	187	190
7 letters	268	280	279	289
1 syllable	115	117	105	79
2 syllables	368	275	386	479
3 syllables	102	100	98	45
4 syllables	15	8	12	0
2 phonemes	4	0	0	0
3 phonemes	39	33	11	12
4 phonemes	120	133	77	104
5 phonemes	186	203	197	158
6 phonemes	172	164	223	223
7 phonemes	71	64	92	103
8 phonemes	8	3	0	0

Table 2.5 *Numbers of items presented in each of the above conditions (cells)*

		Lexical task				Symmetry task			
		Lexicality		Bigram freq		Lexicality		Bigram freq	
		NonW	Word	High	Low	NonW	Word	High	Low
Switch	Mean RTs in ms (% errors)	934 (9.2)	838 (10.9)	893 (10.0)	879 (10.1)	1022 (6.5)	1025 (5.0)	1018 (5.5)	1030 (6.0)
Repeat	Mean RTs in ms (% errors)	880 (5.7)	774 (7.6)	833 (7.0)	820 (6.4)	959 (5.2)	953 (4.0)	952 (4.4)	960 (4.8)
Switch cost	Mean RTs in ms (% errors)	54 (3.5)	64 (3.3)	60 (3.0)	59 (3.7)	63 (1.3)	73 (1.0)	66 (1.1)	70 (1.2)

Table 2.6 *RTs and error rates by switch, task, lexicality and BF*

		Lexical task		Symmetry task	
		Congruent	Incongruent	Congruent	Incongruent
Switch	Mean RTs in ms (% errors)	881 (4.7)	891 (15.4)	1010 (3.3)	1037 (8.2)
Repeat	Mean RTs in ms (% errors)	822 (4.9)	831 (8.5)	954 (3.7)	958 (5.5)
Switch cost	Mean RTs in ms (% errors)	59 (-0.2)	60 (6.9)	57 (-0.4)	79 (2.7)

Table 2.7 *RTs and error rates by switch, task and congruency*

PCA Compo-Nent	Variance accounted for	Peaking at/ High loadings between	Significant effects in ANOVA	df	F	p
1	15.2%	106 ms	switch switch x region switch x region x lat BF x region	1,17 3,51 6,102 3,51	5.63 23.42 2.71 4.64	< 0.05 < 0.01 < 0.05 < 0.05
2	8%	158 ms	switch x region lexicality lexicality x BF lex x region x lat high BF items: lexicality low BF items: lexicality lexicality x region x lat	3,51 1,17 3,51 6,102 1,17 1,17 6,102	16.59 12.24 5.36 2.75 5.52 16.37 3.65	< 0.001 < 0.01 < 0.05 < 0.05 < 0.05 < 0.01 < 0.05
3	23.5%	195 – 250 ms	switch x lat lex x region BF x region	2,34 6,102 6,102	4.69 9.22 6.21	< 0.05 < 0.01 < 0.05
4	12.8%	300 - 400 ms	switch x BF switch x region switch x lat switch x region x lat lexicality x region lexicality x lat repeat only: BF BF x lat	1,17 3,51 2,34 6,102 3,51 2,34 1,17 2,34	4.53 5.38 6.3 2.86 104.38 7.61 13.55 4.09	< 0.05 < 0.05 < 0.01 < 0.05 < 0.001 < 0.01 < 0.01 < 0.05
5	39.9%	400 – 600 ms	switch x BF switch x lat sw x BF x region x lat lexicality	1,17 2,34 6,102 1,17	5.15 13.11 2.61 27.56	< 0.05 < 0.001 < 0.05 < 0.001

			lexicality x region	3,51	12.41	< 0.001
			lexicality x lat	2,34	6.06	< 0.01
			lexicality x region x lat	6,102	3.92	< 0.05
			switch only:			
			BF x region x lat	6,102	3.44	< 0.05
			repeat only:			
			BF	1,17	5.55	< 0.01
			BF x region x lat	6,102	2.81	< 0.05

Table 2.8 *Statistics of PCA components of post-stimulus ERPs from the lexical decision task, (Exp.2)*

PCA Compo-Nent	Variance accounted for	Peaking at/ High loadings between	Significant effects in ANOVA	df	F	p
1	13.1%	110 ms	switch	1,17	19.2	< 0.001
			switch x region	3,51	24.62	< 0.001
			switch x lat	2,34	8.44	< 0.01
			switch x region x lat	6,102	5.29	< 0.05
			switch x lexicality	1,17	7.33	< 0.05
			switch x lex x lat	2,34	4.23	< 0.05
			switch only:			
			lexicality	1,17	6.23	< 0.05
2	7.1%	160 ms	switch x lexicality	1,17	3.74	0.07
			switch x lat	2,34	6.02	< 0.01
			switch x region x lat	6,102	3.64	< 0.01
			lexicality	1,17	4.74	< 0.05
			lexicality x lat	2,34	4.01	< 0.05
			switch only:			
			lexicality	1,17	6.77	< 0.05
			repeat only:			
			lexicality x laterality	2,34	5.55	< 0.05
			lexicality x BF x lat	2,34	3.6	< 0.05
3	28.1%	200 - 300 ms	switch x region	3,51	7.14	< 0.01
			switch x BF	1,17	5.88	< 0.05
			switch x lex x BF	1,17	5.43	< 0.05
			lexicality x region	3,51	3.92	< 0.05
			BF x region	3,51	5.62	< 0.05
			switch only:			
			BF	1,17	5.85	< 0.05
			repeat only:			
			lexicality	1,17	7.15	< 0.05
4	3.5%	380 ms	switch	1,17	4.92	< 0.05
			switch x lex x BF	1,17	6.23	< 0.05
			lexicality x region	3,51	36.16	< 0.001
			lexicality x reg x lat	6,102	7.88	< 0.001

			BF x region	3,51	7.58	< 0.01
			BF x lat	2,34	5.39	< 0.01
			switch only:	1,17	4.52	< 0.05
			lexicality x BF	3,51	24.05	< 0.001
			lexicality x region	6,102	6.33	< 0.001
			lexicality x reg x lat			
			repeat only:	3,51	41.79	< 0.001
			lexicality x region	6,102	4.06	< 0.01
			lexicality x reg x lat	2,34	4.06	< 0.05
			BF x lat			
5	42.5%	400 – 600 ms	switch	1,17	9.85	< 0.01
			switch x laterality	2,34	4.34	< 0.05
			switch x region	3,51	19.29	< 0.001
			switch x region x lat	6,102	10.01	< 0.001
			lexicality	1,17	12.58	< 0.01

Table 2.9 *Statistics of PCA components of post-stimulus ERPs from the symmetry task (Exp.2)*

PCA Compo-Nent	Variance accounted for	Peaking at/ High loadings between	Significant effects in ANOVA	df	F	p
1	5.6%	112 ms	switch x region switch x task x lat	3,51 2,34	6.09 7.95	< 0.05 < 0.01
2	5.5%	180 ms	task x switch switch x region switch x lat lexical decision task: switch x region switch x lat symmetry task: switch switch x region	1,17 3,51 2,34 3,51 2,34 1,17 3,51	5.02 19.3 5.34 5.53 9.17 12.25 18.15	< 0.05 < 0.001 < 0.05 < 0.05 < 0.01 < 0.01 < 0.001
3	18.9%	280 ms	switch switch x region switch x lat switch x region x lat	1,17 2,34 2,34 6,102	20.33 20.55 7.68 5.44	< 0.001 < 0.001 < 0.01 < 0.01
4	40.2%	380-500 ms	switch x lat switch x region x lat	2,34 6,102	6.73 5.29	< 0.01 < 0.001
5	21.7%	550-800 ms	switch switch x region switch x lat switch x region x lat switch x task x lat	1,17 2,34 2,34 6,102 2,34	29.7 49.7 8.22 3.22 5.29	< 0.001 < 0.001 < 0.01 < 0.05 < 0.05

Table 2.10 *Statistics of PCA components from ERPs of the cue interval, (Exp.2)*

3

Unprepared switching between lexical and symmetry tasks

The experiments reported in Chapter 2 were motivated by the idea of localising the residual switch cost — i.e. the switch cost that remains even after sufficient time to reconfigure the cognitive system for a change of task — within the latent interval. They showed that switching to a lexical task after 800 ms preparation time resulted in a delay of ERP markers of lexical processing on switch compared to repeat trials, around 200-300 ms after stimulus onset. This is strong evidence for an early locus of the switch cost obtained in these experiments.

The experiment reported in the present chapter was identical to Experiment 1 except that the CSI was 200 ms, so that there was essentially no opportunity for preparation before the stimulus onset. The experiment in this chapter attempted to clarify the following issues. The first was to establish that the switch cost in Experiment 1 was "residual" — i.e. that the participants had engaged in effective preparation during the CSI. The second was to use ERPs in the same way as in Experiment 1 to localise the effect on an unprepared switch on processing and reveal the occurrence of task-set inertia, i.e. activations of the irrelevant task, for comparison to the effects of a prepared switch.

Experiments 1 and 2 used a single long CSI on all trials to ensure a sufficient number of trials for ERP analysis. A critic might point out that provision of a preparation interval is no guarantee that participants use it to prepare. Indeed, Altmann (2004) has argued that a reduction in switch cost cannot be achieved when participants experience only one (long) CSI. However, experiments in our lab (e.g., Monsell & Mizon, under revision) have shown substantial RISC effects in a between-subject design. We believe that participants given a single long CSI will use it to prepare if appropriately instructed and adequately motivated. Moreover, in Experiments 1 and 2 we observed the pre-stimulus ERP signature of task-set preparation that Lavric et al. (2008) found predicted successful reduction of the switch cost. Nonetheless, the acid test is to show that with a CSI too short for preparation, a substantially larger switch cost is obtained.

The second motivation for the experiment was to apply the same two kinds of analysis to the effects of an unprepared switch. The first analysed the latency of the onset of ERP effects associated with lexical access. The second used PCAs to determine the sensitivity to switching and frequency/lexicality of early components. However, there was a strong reason, a priori, for doubting that a latency analysis of the same kind would be possible in the present experiment. It would only work if either essentially the same processes are performed on task-switch and -repeat trials but more slowly on a switch trial, or if any extra process's duration is inserted as an additive stage (in the sense of Sternberg, 1969, 1998). But the concept of task-set reconfiguration precludes the "same processes more slowly" option: TSR constitutes an extra process that, on short CSI trials, has to be carried out during the latent interval. The question is therefore whether it would function as an extra duration inserted cleanly into the processing chain, thus delaying later processes without radically changing their ERP morphology, or in some other way: for example, being carried on in parallel with other processes and competing with them for resources. Or the incompleteness of TSR may degrade the efficiency of task-specific processes relative to their execution on task-repeat trials. Unless the effect is "pure insertion", the additional brain activity added by TSR on switch trials is unlikely to leave any delay to processing detectable as a latency shift in the onset or evolution of the frequency effect. We already know from ERP studies comparing prepared and unprepared switching (Nicholson et al., 2005; Lavric et al., 2008) that lack of preparation fairly radically transforms the post-stimulus ERP, overwriting the general switch-related negatively with the phasic positivity that Lavric et al. (2008) interpreted as resulting from post-stimulus TSR.

Hence we were sanguine about the likelihood of post stimulus TSR manifesting itself as a clean latency shift in the onset of the ERP frequency effect similar to but greater than that in Experiment 1. However, we had higher hopes for other indicators based on the PCA analyses. We could still ask how early switch-sensitivity is detectable relative to frequency-sensitivity in components revealed by PCA on the lexical task trials. And we could still look for evidence of task-set inertia in the effects of frequency on the symmetry task ERP.

Experiment 3

In summary, the paradigm of this experiment was identical to that of Experiment 1 with the exception that the here CSI was only 200 ms (instead of 800 ms). This experiment had four aims:

(1) to provide a behavioural measure of switch cost without preparation for comparison to the prepared switch cost of Experiment 1;

(2) to see whether it is possible to detect a switch-related delay in the onset of the effect of frequency on the ERP for the lexical task, for comparison to that in Experiment 1;

(3) to establish how early, relative to effects of frequency effects of an unprepared switch are detectable in ERP components underlying performance of the lexical task;

(4) to establish whether signs of lexical processing are found on symmetry task trials and whether this activity is larger for switch than repeat trials.

METHOD

Participants

Eighteen right-handed students from the University of Exeter (13 female, 5 male; aged between 18 and 21, mean =19) were paid two course credits for participation supplemented by a bonus payment (max £4) calculated on the basis of their performance (see Procedure, Experiment 1). Participants gave informed consent following the guidelines set by the University of Exeter School of Psychology ethics committee.

Stimuli and Procedure

The same stimuli, paradigm and procedure were used as in Experiment 1 (see Figure 2.1 in Chapter 2) with one modification: the cue to stimulus interval was reduced to 200 ms (whilst keeping the RSI of 1600 ms the same).

EEG and ERPs

EEG recording equipment and settings as well as ERP pre-processing steps were the same as in Experiment 1. Excluding error trials, trials following errors and the first trial of each block, the EEG was segmented into a 1000 ms epoch, time-locked to the cue and baseline-corrected relative to the average amplitude of the 100 ms preceding the cue. Resulting segments were visually inspected for artifacts. Segments containing ocular, muscle,

movement and other artifact were removed manually. The remaining EEG segments were averaged for every participant and experimental condition.

Two temporal principal components analyses were run (PCA) (Donchin & Heffley, 1978) on an electrode (62) x condition (4 levels) x subjects (18) x time-points (500) matrix, with time-points as the predictor variables. Given the briefness of the CSI, we submitted time points (corresponding to the 500 Hz sampling rate) of the interval comprising the 200 ms CSI and the first 800 ms of the post-stimulus latent interval to a single PCA. One such PCA was run on amplitudes from the semantic task, another on amplitudes from the symmetry task. Both PCAs included the conditions task transition (switch, repeat) and frequency (LF, HF). For details of PCA parameters and subsequent analysis of components please see methods of Experiment 1.

RESULTS

Behavioural results

Mean correct RTs and error rates for all possible combinations of switch/repeat, task, frequency and symmetry are given in Table 3.1 (see also Figure 3.1). For the symmetry task, only the RTs of Go trials (62.5% of trials) were included. The first trial of each block (unclassifiable as 'switch' or 'repeat') and trials preceded by errors were discarded from the behavioural and ERP analyses. A switch (2) by task (2) by frequency (2) ANOVA on RTs found significant main effects of switch, $F(1, 17) = 73.81; p < 0.001$, task, $F(1, 17) = 15.55; p < 0.01$ and frequency, $F(1, 17) = 22.10; p < 0.001$. Responses were slower on switch trials than on repeat trials, faster for high frequency than for low frequency words and faster in the semantic task than in the symmetry task. The effect of frequency (LF vs. HF) was larger in the semantic task (39 ms) than on the go trials of the symmetry task (8 ms), $F(1, 17) = 8.9; p < 0.01$. To examine the effect of symmetry on RTs of the semantic task (not possible for symmetry task since proportion of trials are Nogo) a separate ANOVA was run including the factors switch, symmetry and frequency. This revealed the expected main effects of switch, $F(1, 17) = 67.18; p < 0.001$ and frequency, $F(1, 17) = 23.55; p < 0.001$ as well as a reliable effect of symmetry, $F(1, 17) = 10.66; p < 0.01$ with asymmetrical words being responded to faster (838 ms) than symmetrical words (880 ms). Symmetrical words require withholding the response in the symmetry task hence slower responses to them on semantic task trials suggests, as in Experiment 1, interference from the irrelevant task set.
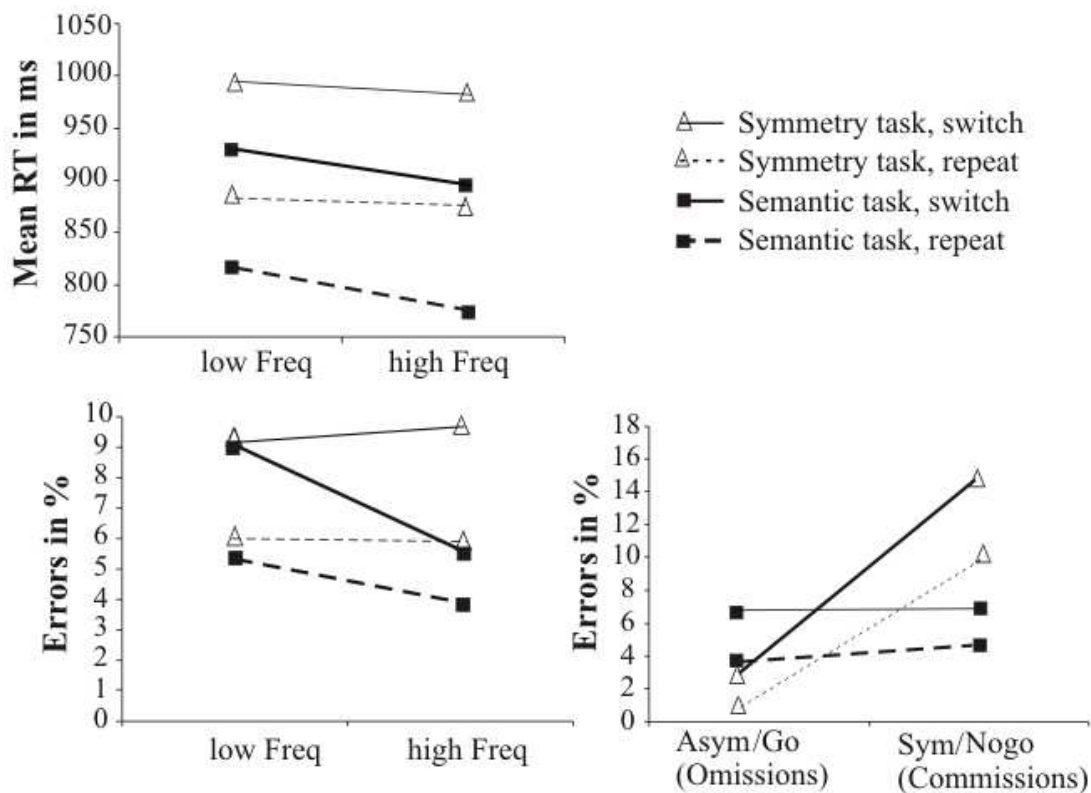
Figure 3.1 *RT and error rates by switch, task and frequency (left); errors by switch, task and GoNogo (right)*

An ANOVA on the error rates including the factors switch, task, frequency and symmetry found reliable effects of switch, $F(1, 17) = 18.14$; $p < 0.01$, symmetry, $F(1, 17) = 38.2$; $p < 0.001$, and reliable interactions between task and symmetry, $F(1, 17) = 18.91$; $p < 0.001$ and task and frequency, $F(1, 17) = 9.91$; $p < 0.01$. To investigate these effects in more detail, separate ANOVAs were run for the two tasks. In the semantic task, the main effects of switch, $F(1, 17) = 13.93$; $p < 0.01$ and frequency, $F(1, 17) = 15.89$; $p < 0.01$ were reliable, as was the interaction between switch and frequency, $F(1, 17) = 6.42$; $p < 0.05$ with a larger error switch cost for low frequency (3.7%) compared to high frequency words (1.7%). In the symmetry task, reliable effects of switch, $F(1, 17) = 14.31$; $p < 0.01$ and symmetry, $F(1, 17) = 28.1$; $p < 0.001$ were found, the latter reflecting more commission errors on Nogo trials (12.9%) than incorrect (or lack of) responses on Go trials (2.5%).

Thus a similar pattern was seen as for Experiment 1, but with larger switch costs. To examine the effects of CSI, ANOVAs were run including the RT and error rates of both experiments (with the factors switch, frequency, task and experiment). I report only the interactions with experiment (see Figure 3.2A and B). The most important is the reliable interaction between switch and experiment, $F(1, 34) = 15.16$; $p < 0.001$. Since the experiments differed only in the duration of the CSI, this interaction reflects an overall reduction in switch cost from 113 ms with a 200 ms CSI (Experiment 2) to 51 ms in the 800 ms CSI (Experiment 1). In the semantic task switch cost reduced from 117ms in the short to 50 ms in the long CSI, $F(1, 34) = 13.33$; $p < 0.01$; in the symmetry task it was reduced from 108 ms to 52 ms, $F(1, 34) = 5.39$; $p < 0.05$. There were no reliable differences in the effects of frequency on the semantic task RTs for short CSI (39 ms) versus long CSI (30 ms), nor for the symmetry task RTs (8 versus 7 ms). The effects of symmetry on the semantic task were larger in Experiment 2 (42 ms) compared to Experiment 1 (19 ms) but not reliably so, $F(1, 34) = 2.14$; $p = 0.15$.
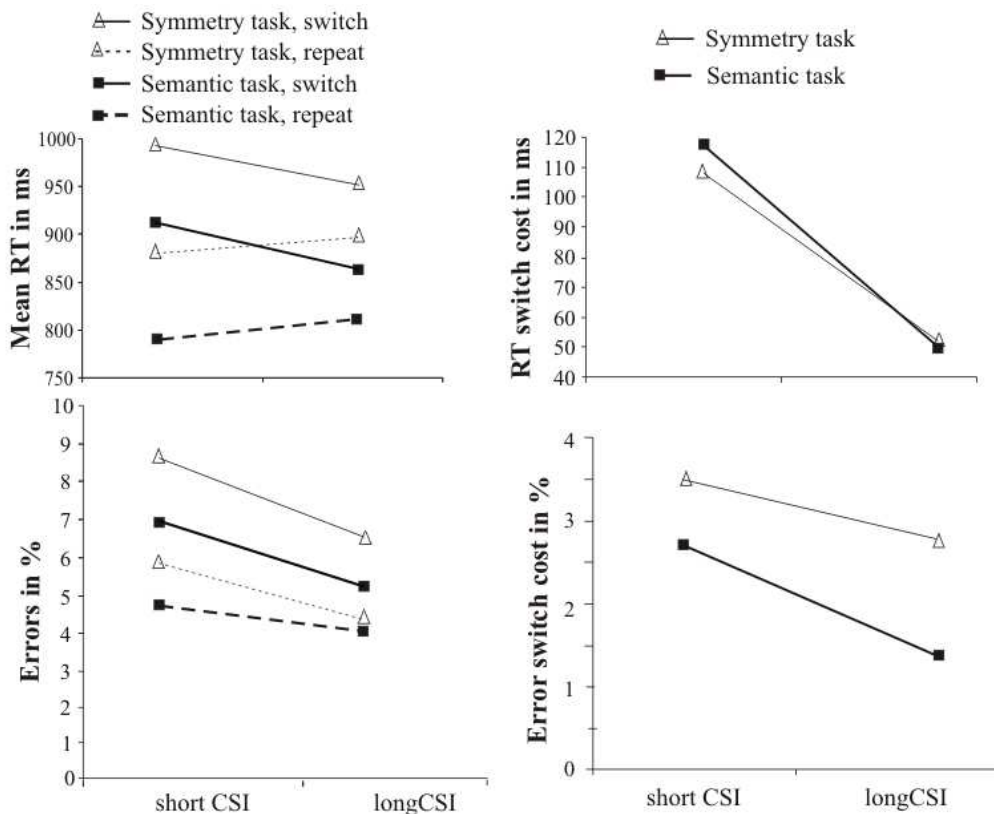
Figure 3.2 *RTs and error rates by switch, task and CSI (left), RT and error switch cost by task and CSI*

For error rates the effects of symmetry differed reliably between the two studies with more errors for symmetrical (nogo) vs. asymmetrical (go) stimuli in Experiment 2 (a difference of 5.5%) compared to Experiment 1 (2.5%), $F(1, 34) = 7.47$; $p < 0.05$. There were no reliable differences in frequency effects in the semantic task (short CSI 2.4%, long CSI 1.7%) or the symmetry task (short CSI 0%, long CSI -0.2%).

ERPs from the semantic task

Latency analysis. To determine whether a unprepared switch results in a simple delay in the onset of lexical processing we computed the grand-average low minus high frequency difference waveforms and GFP difference waves for switch and repeat trials separately (see Figure 3.4 for electrodes Pz, POz, and GFP, and Figure 3.3 for the waveforms from which the differences are obtained). Unlike in Experiment 1, the difference waves do not suggest a simple delay in the evolution of the ERP frequency effect. Instead the amplitude of the frequency effect appears to be substantially suppressed by switching. Hence a latency analysis of the frequency effect similar to that for Experiments 1 and 2 could not be carried out.
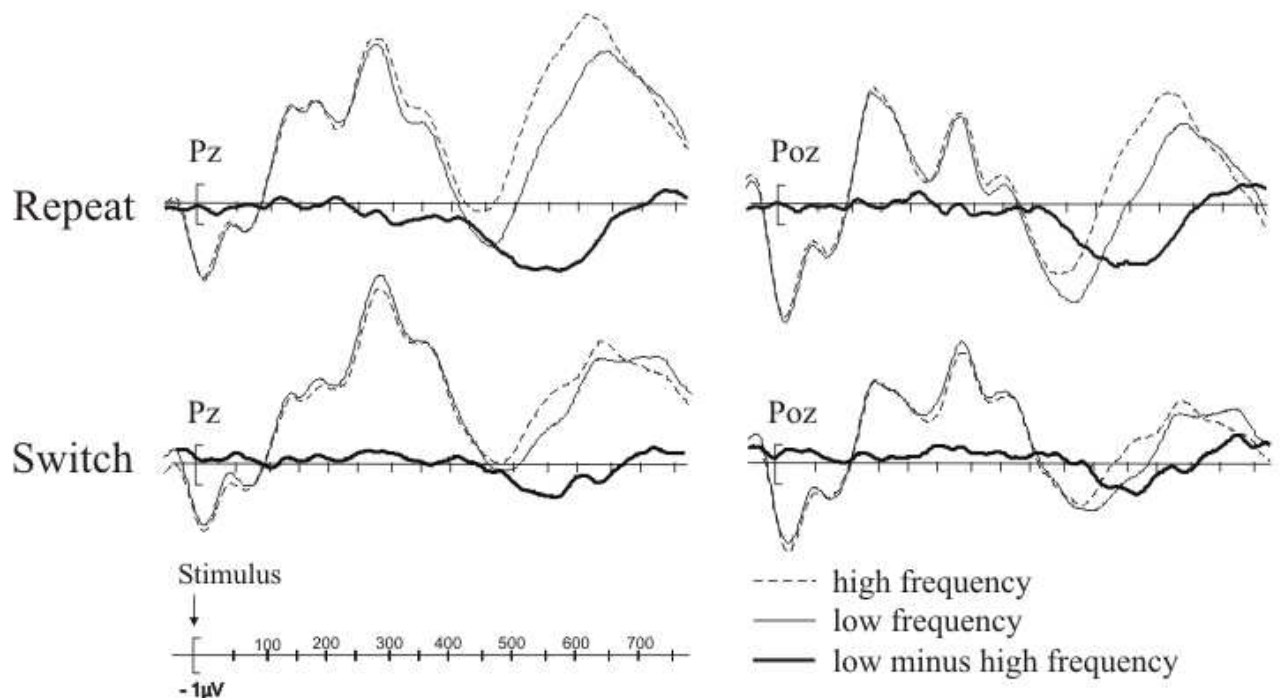
Figure 3.3 *ERPs for switch- and repeat high and low frequency trials for the semantic task*
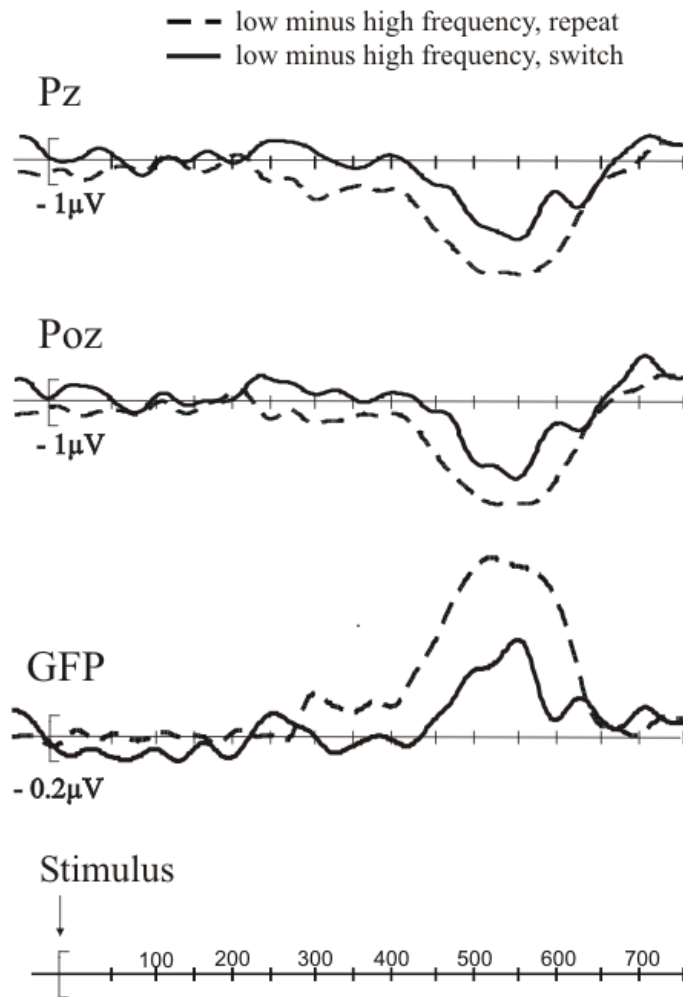
Figure 3.4 *Low minus high frequency difference waveforms and GFP difference waves for the semantic task*

PCA-based amplitude analyses

Sample average ERPs for switch- and repeat high and low frequency trials for the semantic task are shown in Figure 3.3. The PCA on the semantic task with conditions switch/repeat and frequency (HF, LF) identified eight components (shown in Figure 3.5) explaining at least 2% of the variance in the waveforms over all scalp electrodes, five of which (solid lines in Figure 3.5) were sensitive to switching and/or frequency (see Table 3.2).

Of these, the first two components, peaking at ~150ms and 190ms post-stimulus showed more negative amplitudes for switch vs. repeat trials in anterior regions. Component 3 had high loadings between 200- 350ms post-stimulus and captured a

widespread posterior positivity for switch. Its topography strongly resembles that of the late posterior positivity found in the last few hundred milliseconds of long CSIs. At the same time (i.e. in the same component) local effects of word frequency were detected; here amplitudes were more positive for LF vs. HF maximal in left parietal regions (a topography different from that observed for early frequency effects in Experiment1). The next component had high loadings between 350- 530ms (peak at 450ms) post-stimulus and showed a reliable interaction between switching and frequency. Analyses for switch and repeat trials separately revealed highly reliable frequency differences for repeat trials with more negative amplitudes for low vs. high frequency words in central and posterior regions of the scalp. For switch trials frequency differences were not reliable, $(F(1, 17) = 2.3; p = 0.15)$. Finally, a small component (3% of variance explained), peaking at 550ms, was

Figure 3.5 *PCA components and their topographies of the semantic task*

sensitive to frequency on both switch and repeat trials; amplitudes for LF words were more negative than HF words in posterior regions. The same component also captured a widespread negativity for switch similar to the switch negativity found in long CSI post-stimulus intervals.

In summary, switching affected the average ERP waveforms from about ~150 ms post-stimulus until almost the end of the interval. The most prominent (i.e. widespread) effects were a posterior positivity for switch ~200- 350 ms post-stimulus, which was similar to the one found in the later parts of long CSIs and a posterior negativity for switch between 350- 530 ms post-stimulus similar to the one found at this latency in post-stimulus intervals after a long CSI (see Figure 2.6 in Chapter 2). Local frequency differences were detected at the same latency. The most prominent frequency effect - a greater negativity for low vs. high frequency words in all but anterior regions- emerged ~350 ms (peaking ~450 ms) post-stimulus but was only reliable on repeat trials. The component peaking about 100 ms later also captured this frequency difference, here for both trial types, switch and repeat. Hence, effects of switching (as reflected in components 1 and 2) were reliable before first effects of frequency emerged (component 3). The typical effect of frequency (negativity for LF, as observed in Experiment 1 and previous studies) appears larger and reaches its maximum earlier (see Figure 3.4) on repeat than on switch trials.

ERPs from the symmetry task
Sample ERP waveforms of symmetry task, switch- and repeat high and low frequency trials in electrodes Cz and Pz are shown in Figure 3.6. PCA on amplitudes of the symmetry task (with conditions switch/ repeat and low/high frequency) identified 7 components (shown in Figure 3.7) that explained at least 2% of the variance, five of those (solid lines) being sensitive to switching and/or frequency (see Table 3.3 for statistical analysis). In this task, the first switch sensitive component was found already in the cue interval, peaking 180 ms after cue onset. It seems to result from a larger N1 (to the cue) for switch than repeat trials. The next switch sensitive component peaking ~150 ms post-stimulus also showed more negative amplitudes for switch vs. repeat in posterior regions. This was, however, caused by more positive amplitudes (larger P1) for repeat than switch trials. Around 250 ms amplitudes became more positive for switch trials, here still confined to the right hemisphere. In the next component (high loadings between 280-500 ms post-stimulus) the
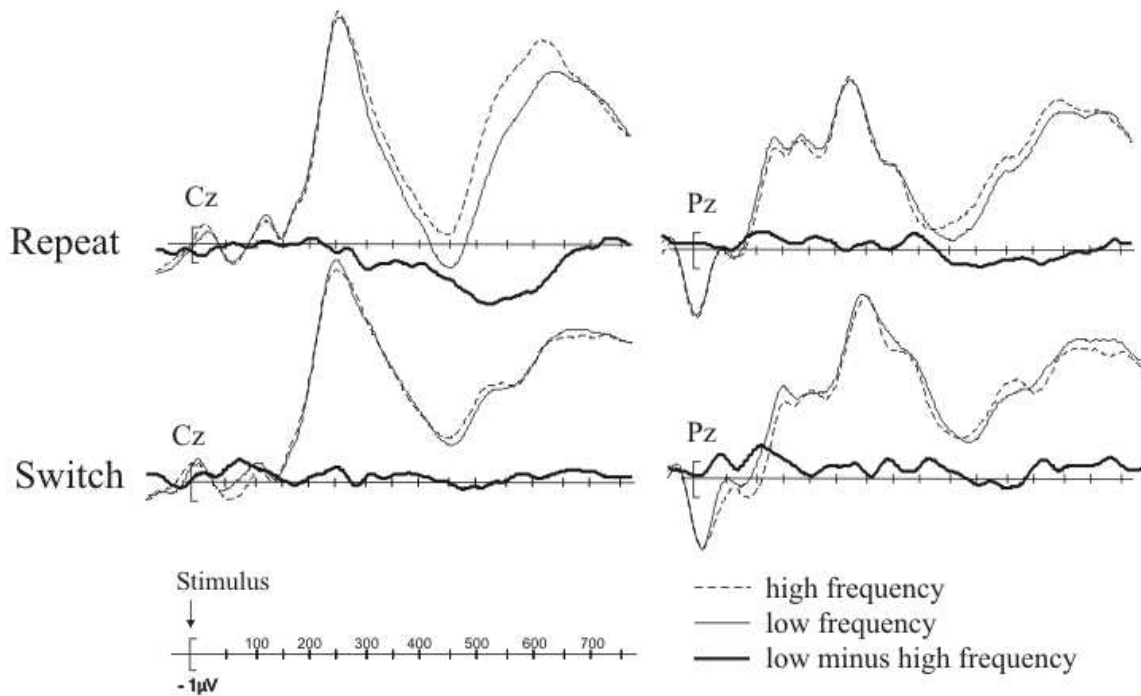
Figure 3.6 *ERPs for switch- and repeat high and low frequency trials for the symmetry task*

switch positivity covered large areas of the central and posterior scalp. As in the semantic task, this modulation resembles the component that we usually observe in the last few hundred milliseconds of long preparation intervals, the posterior positivity for switch. The last component with high loadings from 500 ms post-stimulus onwards was sensitive to switching with more negative amplitudes for switch vs. repeat in right hemispheric and central regions of the scalp. This somewhat atypical (more right-lateralised) topography of the switch negativity might be caused by an overlap with the immediately preceding switch positivity which was maximal in left posterior regions. The last PCA component further showed an interaction between switching, frequency, region and laterality. Separate analyses for switch and repeat trials revealed a reliable interaction between frequency, region and laterality on switch trials, while on repeat trials the frequency by laterality interaction was only marginally reliable. Frequency effects were further of different, in some regions opposite, polarity for switch and repeat trials suggesting differences in the way the irrelevant dimension interfered (or was dealt with) on the two trial types.
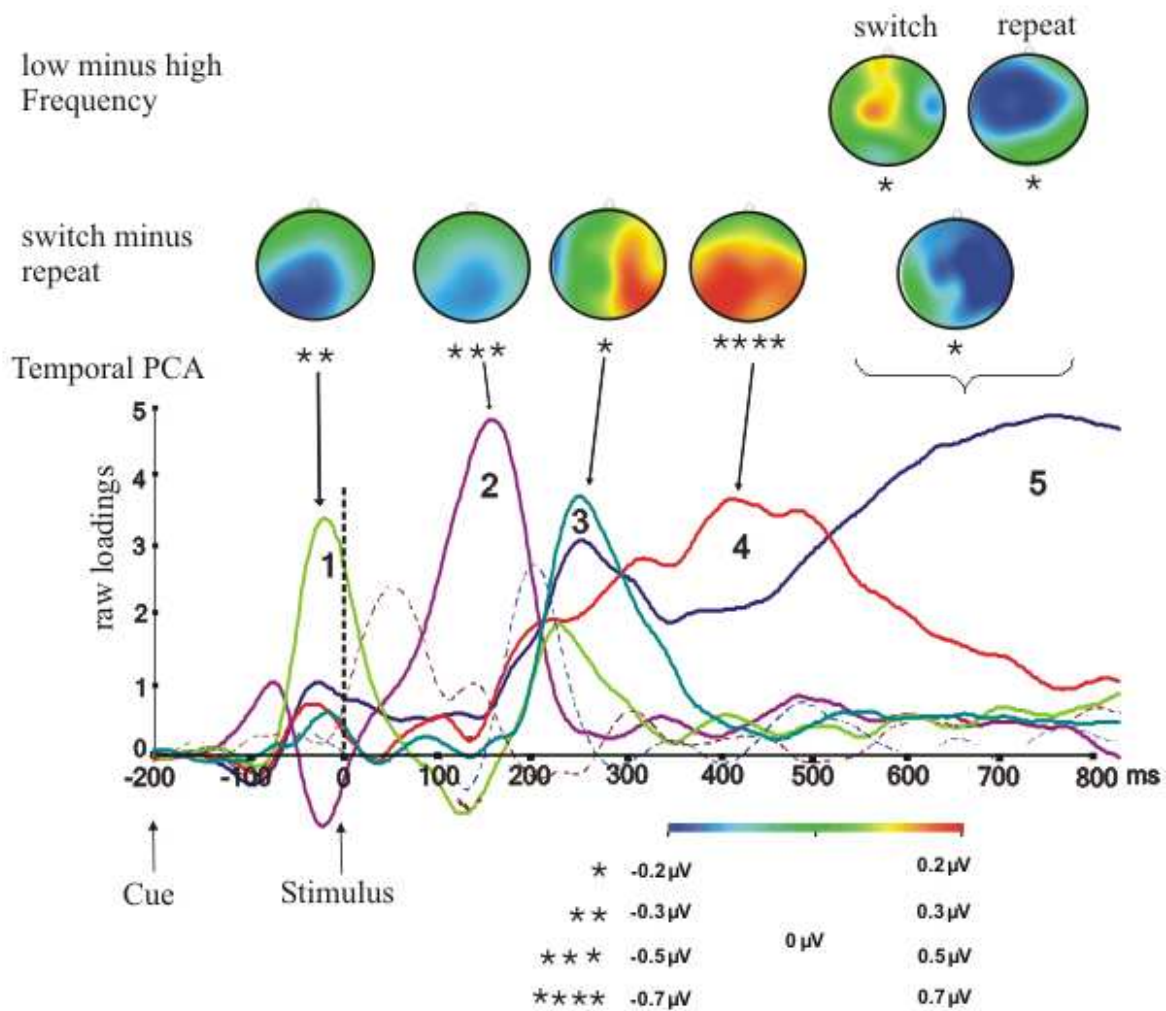
Figure 3.7 *PCA components and their topographies of the symmetry task*

In summary, switching tasks affected waveforms throughout the whole interval; as in the semantic task, the most prominent modulations were a positivity for switch between ~280-500 ms post-stimulus that covered large areas of the posterior scalp and a later, widespread negativity for switch. Significant effects of word frequency were detected only towards the end of the post-stimulus interval (from ~500 ms onwards) where they were (slightly) larger and of different polarity for switch than repeat trials.

DISCUSSION

ERP studies of task switching that compared waveforms of short and long CSI blocks (Nicholson et al., 2005; Lavric et al, 2008) have observed that the posterior switch positivity usually found in the later part of a preparation interval (from about 400 ms after cue onset onwards), appears also to be present when CSIs are short, but now displaced into

in the post-stimulus latent interval, emerging at a similar latency following cue onset. The present study confirmed these findings; in both tasks a posterior switch positivity emerged ~400 ms after cue onset that is ~200 ms post-stimulus. This is consistent with the theory that the part of the switch cost that can be mitigated by preparation reflects a TSR process that is necessary on switch trials but can be carried out before the stimulus if time permits. Let us consider the other outcomes in relation to the four aims laid out at the end of the introduction.

(1) Comparison of switch costs with a 200 ms CSI to those obtained in Experiment 1 with an 800 ms CSI. The overall switch cost in this experiment was 113 ms (3.1 %), compared to 51 ms (2.1 %) in Experiment 1. This reliable and substantial (55%) RISC is comparable to the RISC effect obtained in experiments which extend the CSI well into the asymptotic portion of the preparation functions (e.g. Monsell & Mizon, 2006). This strengthens our argument that Experiment 1 truly investigated the residual switch cost.

(2) Estimation of any delay in the onset of the ERP frequency effect on switch trials. The morphology of the ERP frequency effects for switch and repeat trials was dissimilar in a way that allowed no assessment of such a delay; the amplitude of the frequency effect was much smaller on switch than on repeat trials. Following through the argument in the introduction, this implies that the extra processing resulting in the amplified RT switch cost did not merely prolong one or more processes in the same stage architecture as used on repeat trials, nor did it cleanly insert an extra processing duration. Rather it changed processing in a more radical way. And, by the same token, the fact that we could detect a latency effect in Experiments 1 or 2 suggests that prepared switching either slows processing without changing the processing architecture, or inserts an extra processing stage.

(3) Use of PCA to assess the earliness of the impact of switching on the processes underlying the lexical task. Having frequency effects as a marker for lexical access allowed us to examine the components discovered by PCA to ask where switch effects appear relative to frequency effects. Several components (components 1 and 2, Figure 3.5) showed sensitivity to a task switch preceding the first component that showed a frequency effect. From about ~200 ms onwards (component 3), a posterior positivity for switch emerged which is thought to reflect TSR. At the same time first frequency differences were observed. This suggests that TSR is not cleanly inserted as an extra processing stage on switch trials but rather competes with lexical access for resources.

It seems to change the processes underlying the early frequency effects in a qualitative way as suggested by a topography that has not been reported before. Further, only weak frequency differences are observed on switch trials between 350-500 ms post-stimulus (component 4) while on repeat trials they are already large at that time. This could suggest that lexical access is delayed on switch trials or its efficiency is compromised. However, it is also possible that we cannot detect its exact evolution in the ERP because it is masked by the preceding positivity which is particularly large on switch trials.

(4) Effects of frequency on the symmetry task. The earliest evidence of processing of the irrelevant task attributes, i.e. an effect of word frequency on ERPs in the symmetry task was apparent only in a relatively late component ~500 ms post-stimulus. They were slightly larger on switch trials though their magnitude was not as distinctly different to that on repeat trials as observed in Experiment 1. Although it is still unclear to what extent stimulus caused interference can be reduced with preparation, intuitively one would have expected conflict from the irrelevant task to be larger when switching without than with time to prepare. One tentative speculation to explain the observed pattern of results is based on the difficulty of exactly determining the processes that underlie ERP waveforms, particularly when their temporal overlap is substantial. Frequency differences in the symmetry task in Experiment 1 were maximal in the latency range of the N400 (~400 ms). In this study two positivities are present in this latency range, the switch positivity maximal from ~200-400 ms and the subsequent P3 maximal from ~400-600 ms, which could possibly mask frequency differences expressed in more negative N400 amplitudes. This would also explain why the topography of frequency effects in the symmetry task for either, switch and repeat, is quite different to what we have observed in the semantic task of this study or the semantic and symmetry task of the experiments in Chapter 2. Particularly for switch trials, on which the preceding positivity is large, N400 differences might be underdetected or distorted.

To sum up, there is evidence of lexical access from about ~500ms onwards in the symmetry task, and slightly more so on switch compared to repeat trials. There is, however, a good chance that earlier frequency effects, particularly on switch trials are underdetected or distorted due to an overlap of multiple processes/ERP components. Otherwise we would be in the odd positions of claiming more activation of the irrelevant task after preparation than without.

Appendix Chapter 3: Data tables

		Semantic task				Symmetry task			
		Frequency		Symmetry		Frequency		Symmetry	
		High	Low	Asym	Sym	High	Low	Asym (Go)	Sym (Nogo)
Switch	Mean RTs in ms (% errors)	894 (5.6)	931 (9.1)	892 (7.3)	946 (7.4)	984 (9.7)	997 (9.2)	991 (3.4)	-- (15.4)
Repeat	Mean RTs in ms (% errors)	775 (3.9)	816 (5.4)	785 (4.2)	813 (5.1)	881 (5.8)	884 (6.0)	883 (1.5)	-- (10.4)
Switch cost	Mean RTs in ms (% errors)	119 (1.7)	115 (3.7)	107 (3.1)	133 (2.3)	103 (3.9)	113 (3.1)	108 (1.9)	-- (5.1)

Table 3.1 *RTs, error rates and switch costs of experiment 3*

PCA Compo-nent	Variance accounted for	Peaking at/ High loadings between	Significant effects in ANOVA	df	F	p
1	13%	150 ms	switch switch x region	1,17 3,51	9.94 7.99	< 0.01 < 0.01
2	2.6%	390 ms,	switch x region	3,51	8.17	< 0.01
3	15%	250 ms	switch switch x region switch x lat switch x region x lat freq x region x lat	1,17 3,51 2,34 6,102 6,102	19.68 20.9 17.49 8.81 3.85	< 0.001 < 0.001 < 0.001 < 0.01
4	19%	450 ms	switch x frequency switch x freq x lat switch x region x lat frequency freq x region x lat switch x freq x reg x lat repeat only: frequency	1,17 2,34 6,102 1,17 6,102 6,102 1,17	4.56 3.42 2.69 13.44 2.73 2.48 24.52	< 0.05 < 0.05 < 0.05 < 0.01 < 0.05 < 0.05 <0.01
5	3%	550 ms	switch switch x region switch x lat switch x region x lat frequency freq x region freq x lat freq x region x lat	1,17 3,51 2,34 6,102 1,17 3,51 2,34 6,102	51.81 10.81 17.92 12.75 15.86 21.99 8.09 8.63	< 0.001 < 0.01 < 0.001 < 0.001 < 0.001 < 0.001 < 0.01 < 0.001

Table 3.2 *Statistics of PCA components from the semantic task, (Exp. 3)*

PCA Compo-nent	Variance accounted for	Peaking at/ High loadings between	Significant effects in ANOVA	df	F	p
1	5.2%	-20 ms	switch switch x region	1,17 3,51	4.61 5.35	< 0.05 < 0.05
2	11%	150 ms	switch switch x region switch x lat switch x region x lat	1,17 3,51 2,34 6,102	11.69 4.02 5.51 3.53	< 0.01 < 0.05 < 0.01 <0.05
3	6.6%	240 ms	switch x lat	2,34	5.92	< 0.01
4	20.4%	280-500 ms	switch switch x region switch x region x lat	1,17 3,51 6,102	23.59 9.75 7.89	< 0.001 < 0.01 < 0.001
5	43%	500-800 ms	switch switch x lat switch x freq x lat switch x freq x reg x lat switch only: freq x region x lat repeat only: freq x lat	1,17 2,34 2,34 6,102 6,102 2,34	5.77 4.51 3.91 4.58 3.36 3.23	< 0.05 < 0.05 < 0.05 < 0.05 < 0.05 = 0.052

Table 3.3 *Statistics of PCA components from the symmetry task, (Exp. 3)*

4

An attempt to detect a switch-induced processing delay in a face task

The experiments reported in Chapter 2 investigated which stage of task processing is affected by a prepared switch to a task from another requiring attention to a different attribute of the stimulus but the same distribution of spatial attention. We chose lexical tasks (semantic decision and lexical decision) because previous literature had suggested that markers of early stages of lexical access could be detected in modulations of the ERP waveform. This was important because it provided the opportunity to investigate early effects of switching, preceding the response selection stage, which has been widely argued to be the main locus of the residual cost. As described in Chapter 2, task switching delayed lexical processing as early as ~200 ms after stimulus onset suggesting a much earlier locus of the residual switch cost than many theorists have assumed.

The experiment reported in this chapter was an attempt to generalize this research strategy and conclusion to a different domain. An important requirement of the task to be used is that it should elicit an early marker of processing which is detectable in the ERP and whose latency can be assessed. A review of the ERP literature in search of non-lexical tasks that show early ERP effects suggested face processing tasks as a solution. In particular, Eimer and colleagues have reported several studies investigating differences in face processing depending on whether the face has an emotional or neutral expression. ERP differences between these types of facial expression appear at around 120-180 ms post-stimulus (Eimer & Holmes, 2002, Eimer, Holmes, & McGlone, 2003, Eimer & Holmes, 2007). This *emotion expression effect* (EEE) seemed to provide a suitable candidate for an early ERP marker.

The effect is characterized by a positivity for emotional vs. neutral faces with a fronto-central distribution. It is followed by a more broadly distributed positivity starting around 250 ms, stretching throughout the whole post-stimulus interval (1000 ms). The later effect is thought to reflect higher-level processing such as the conscious evaluation of the

emotional content. The processes underlying the early ERP effect seem somewhat less clear. In a recent review Eimer & Holmes (2007) discussed findings of a number of ERP studies on emotional face processing, linking them with fMRI findings, with particular focus on the early effect. The brain regions consistently activated during the processing of emotional face expressions and other types of affective stimuli seem to constitute an interconnected network including the amygdala, the orbitofrontal cortex and the ventral striatum, and higher cortical areas such as the somatosensory cortex, the anterior cingulate cortex and the medial frontal cortex (see Adolphs, 2002, 2003 for reviews). Whilst limbic structures such as the amygdala are thought to be activated during the rapid classification of emotional content of a visual stimulus, higher cortical regions are thought to be activated when a conscious representation of the emotional content is formed which is then used for the strategic control of behaviour (Adolphs, 2003). The earliness of the emotion-related ERP effect might suggest that it reflects the rapid, pre-attentive assessment of emotional content as implemented by limbic structures such as the amygdala. It is, however, highly unlikely that the ERPs were created by activations of the amydala since it is located deep in the brain and has an electrically closed structure. But amygdala activations might be transmitted directly to neocortical areas (Morris et al., 1998) where they could be picked up by EEG electrodes. FMRI findings have shown that limbic structures and connected neocortical regions were emotion-specific (e.g., activations were much greater for fear than happiness) so if the EEE reflects those activations one would expect a similar modulation of ERP amplitude. Eimer, Holmes & McGlone (2003), however, found that the early ERP effects were very similar for six basic emotions. FMRI studies have shown that emotion detection (as measured by amygdala activation) is unaffected by attention (Vuilleumier, Driver & Dolan, 2001). Eimer & Kiss (2007) found that irrelevant fearful faces can bias the distribution of spatial attention. More precisely, the N2pc as a measure of attentional selection was enhanced when fearful rather than neutral faces were presented next to a fixation cross whose infrequent luminance change needed to be detected. This enhancement was smaller on trials when the luminance actually changed suggesting that a concurrent cognitive load reduced the attentional capture. With regards to the EEE Holmes, Vuilleumier & Eimer (2003) found that it was eliminated when faces were at unattended locations and reduced when the face was presented in the fovea but lines to the left and right of it needed to be attended (Eimer et al., 2003). These properties of the EEE led Eimer et al. to suggest that it does require attentive processing, i.e. is not due to pre-attentive

emotional processing and it might hence reflect activity within the neocortex such as the formation of representations of emotional content which are subsequently used for the intentional control of behavior. They do acknowledge that this process might happen in parallel with the (automatic) evaluation of emotional content by the amygdala and other subcortical structures. A recent study by Kiss & Eimer (2008) suggests that at least part of the EEE is caused by a fairly automatic process since a small but reliable EEE was observed when participants had to judge the facial expression (fearful versus neutral) of a subliminally (8 ms) presented face. The fact that their performance was at chance level was taken as evidence that participants were not conscious of the emotional perception.

Findings by Holmes et al. seem to suggest that for the EEE to arise faces need to be at least in the focus of spatial attention. The effects switching will have on the EEE depends on the extent to which the underlying processes are deliberate or automatic. Several options are possible. If the EEE arises from a task-independent emotional reaction process then this process might unfold whenever faces receive appropriate spatial attention. In this case there is no reason to expect a delay of the EEE on a switch trial; and it should also be unaltered by which task is performed. This emotional reaction process might, however, be modulated by the degree of attention to facial features within the current focus of spatial attention (selection of the face "dimension"). Then we might expect the EEE to be delayed after a switch from the letter task, and, due to attentional inertia, to be modulated in opposite directions by switch/repeat within each task - i.e. larger on face task repeat (versus switch) trials and larger on letter task switch (versus repeat) trials. If the EEE arises from a more deliberate (possibly cortical) emotion recognition process that is part of the chain of processes whose durations underlie the specific task we gave participants, then the following is possible: A switch of tasks may slow down the feature encoding process because the emotion recognition process requires attention to facial features and attention is still directed to letter features. As described above, redirecting attention to the facial features should delay the onset of the EEE. A switch of tasks may also slow down the emotion recognition process itself because the process requires resources/attention still directed to the other task. This could diminish or delay the EEE on face switch trials. It is also possible that a switch of tasks may still prolong only response selection because this particular task (apparently unlike the lexical task) is enabled only by modulating the link between the emotion recognition (automatic or deliberate) and response selection. Further,

if both neocortical (deliberate) and subcortical (automatic) activations contribute to the EEE we might also expect amplitude and/or topographical changes if switching suppresses some of the neural generators but not others.

Given Eimer's finding that the EEE is largest when participants attended to both the face and the emotion we decided to make the emotion judgment one of our tasks (rather than e.g., a gender or age judgment). This should maximize the effect and hence make it easier to detect any modulations of it. Another reason for choosing emotion judgment as a task was to ensure that the processing of emotion must be completed — at least to the point of categorization — to allow selection of a response, hence maximizing the chance that this marker will index a stage of task processing prior to response selection.

The next question that arose involved the choice of the other task. Here, we had to decide whether to choose another face processing task (e.g., age, gender, race judgment) or a task that does not involve face processing but nevertheless required a similar distribution of attention. As potential face processing tasks all involve configural processing of (broadly) the same facial features (even though there may be some independence of emotional and structural processing thereafter, Bruce & Young, 1986), it is possible that early effects of a switch will not be seen when switching between such tasks because there is no need to modulate "perceptual" processing when the task switches. Though this would be of interest, it would be of more interest if we had already shown that early processing IS modulated when there is a switch between processing facial features and other perceptual features of the stimulus. Hence, we decided to look at switching between face processing and a non-face task, for which we chose the processing of a superimposed letter for a vowel-consonant discrimination.

As discussed for the lexical tasks in Chapter 2, to avoid inflating the switch cost by adding a component that is due to switching the locus and/or spread of spatial attention it is vital that the other task requires a similar distribution of attention. Having chosen the letter task we also hoped that there might be an early separation between ERPs elicited by vowels and those elicited by consonants. The only ERP studies that have looked at processing differences between vowels and consonants have done so in the context of word recognition (using a lexical decision task with masked priming; Carreiras, Vergara & Perea,

2007; Vergara-Martinez, Perea, Marin, Carreiras, 2010). Since one cannot generalize word recognition effects to the processing of individually presented letters there does not seem any ERP evidence to date providing information about possible differential effects for a single vowel versus a single consonant. One could speculate, however, that given there are fewer vowels in the alphabet and they occur with much higher frequency in the language than (almost all) consonants they might be recognized more easily, which might be reflected in differences in early visual ERP components. If those differences were reliable we could then look how switching delays/modulates this effect.

Further, we hoped to learn from ERPs from the letter task whether there is involuntary processing of facial emotion, and if so whether it is modulated by a task switch, as the task-set inertia account suggests. As noted above there is some uncertainty to what degree the early EEE reflects automatic emotional activation, as opposed to an intention-based formation of a representation of emotional content. The presence of any EEE in the letter task will address this question, and its modulation by switching may provide further evidence for task set inertia. Our previous results suggest that if processing of a particular attribute requires some allocation of resources such processing will occur to a greater extent on the next trial when it was carried out on the previous trial even if it is irrelevant for the current task goal. We saw that lexical activations (frequency and bigram frequency effects) were larger on trials where participants had just switched to the symmetry task versus when they had done the symmetry task on the trial(s) before.

Experiment 4

The stimulus was a picture of a face (emotional or neutral) with a transparent vowel or consonant superimposed. Participants were instructed by an auditory verbal cue either to classify the facial expression as emotional or neutral, or to classify the letter as a vowel or consonant. As in our previous studies we were interested in examining the source of the residual cost, hence participants were given sufficient time to prepare for a task switch (1000 ms) in the majority of the blocks. We also wanted to assess behaviourally whether the switch cost is truly "residual", (i.e. whether participants used the long CSI to prepare). To this end a few short CSI (200 ms) blocks were interspersed through the experiment,

containing enough trials to assess the RISC effect (but not enough for ERP analysis). The main questions this study attempted to address were (1) does switching delay/modulate the early emotional expression effect; (2) if there is a detectable emergence of an ERP difference between vowels and consonants, does switching delay it; (3) is the EEE present in the letter task and/or are there vowel-consonant differences in the face task; (4) if so, to what extent are these modulated by switching?

METHOD

Participants

Twenty right-handed students from the University of Exeter (17 female, 3 male) aged between 18 and 27 (M=19) received two course credits for participation plus a monetary performance bonus (maximum £4 — see Procedure). Participants gave informed consent following the guidelines set by the University of Exeter School of Psychology ethics committee.

Stimuli and Procedure

Photos of ten males and ten females were selected from the NimStim[7] database of emotional faces. For each person, two photos were selected for each kind of facial expression (emotional or neutral), one with mouth open, one with mouth closed, eighty photos in all (see examples in Figure 4.1). Each photo was displayed so as to subtend 4° horizontally and 5° vertically. The emotional expressions were anger or fear (the most expressive was chosen for a particular person), since these emotions elicit the largest ERP differences when compared to a neutral face expression (Eimer & Holmes, 2002, Eimer & Kiss 2007, Eimer & Holmes, 2007). On each photo one of eight letters was superimposed; the vowel A, E, O or U, or the consonant V, S, N or G. A thin outline of the letter (i.e., no fill) was printed in white, upper case Lucinda Console font covering the central regions of the face including eyes and mouth (see Figure 4.1). The letter's size was chosen to match the area of the face attended to judge emotional expression (and guided by some eye-tracking data from our lab on the distribution of fixations for face identification). The size

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7 Development of the MacBrain Face Stimulus Set was overseen by Nim Tottenham and supported by the John D. and Catherine T. MacArthur Foundation Research Network on Early Experience and Brain Development. Nim Tottenham can be contacted at tott0006@tc.umn.edu for more information concerning the stimulus set.

Figure 4.1 *Examples of stimuli*

of the letter varied slightly (from 1.6° to 2.1°) to match the variability in area attended for face processing and to make it harder to anticipate which facial feature will be covered by it in a particular face (see Figure 4.1 for the four variations in size; size increases from left to right). The aim was to approximately match the spread and variability of the focus of visual attention induced by the letter and face tasks and hence minimize the contribution of any inertia in locus or zooming of spatial attention to switch costs.

In the face task, participants indicated whether the facial expression was emotional or neutral by pressing the right or left arrow key, respectively. In the letter task, participants pressed the right key for vowels and the left key for consonants. The sequence of tasks was unpredictable (tasks changed on average on one third of the trials), with task identity indicated on every trial by one of four auditory cues: "emotion" and "feeling" for the face task, and "letter" and "symbol" for the letter task. The cue changed from trial to trial even on task repeat trials to unconfound task changes from cue changes (cf. Monsell & Mizon, 2006). There were 15 blocks with 80 trials; in 12 of those the CSI was 1000 ms, in the remaining 3 it was only 200 ms (20% of trials). Short CSI blocks were interspersed among

long CSI blocks so that they were in positions: 1, 6, 11 (i.e. SLLLLSLLLLSLLLL); 2, 7, and 12; 3, 8, and 13; 4, 9, and14; or 5, 10 and 15 — each for four subjects. The duration of the auditory cues was 320 ms; hence they overlapped into the stimulus interval in the short CSI. The stimulus was displayed until a response was made. The interval between response and the next stimulus was 1800 ms for all but error trials. On those the word "Error" was displayed for an additional 1200 ms after the response. The assignment of individual faces (20 faces with emotional or neutral expression = 40) to trial types (face/letter task by switch/repeat/repeat) was counterbalanced across 40*6 = 240 trials (three blocks). Subjects with even numbers saw a particular face with a particular expression with the mouth open; subjects with odd numbers saw that face and expression with the mouth closed.

The EEG session was preceded by practice comprising four single-task blocks of 24 trials each (two blocks per task) and two blocks with 48 trials of task switching. Following practice, EEG data were acquired in 15 blocks of 80 trials plus one warm-up trial at the start of each block. Participants were instructed to use the cue to prepare for the upcoming task. To encourage effective preparation, an incentive scheme was employed: a score (mean RT/10 + errors*5) was computed for each block and a bonus payment was made for blocks on which the score was lower than a running average of previous blocks.

EEG and ERPs

The EEG set-up and pre-processing procedures were the same as in Experiment 2. ERPs were analysed only for the long-CSI trials. To identify components underlying the ERP we used temporal principal components analysis (PCA) (Donchin & Heffley, 1978) in the same way as in Experiments 1-3. Four PCAs were run on post-stimulus ERPs, two for each task, with time-points as variables; on an electrode (63) x condition (4 levels, see below) x subjects (20) x time-points (300) matrix of cases (observations). One of the PCAs for each task included the conditions switch-repeat and the relevant task dimension (emotional vs. neutral for the face task and vowel vs. consonant for the letter task), the other included switch-repeat and the irrelevant task dimension (vowel vs. consonant for the face task and emotional vs. neutral for the letter task)[8]. One additional PCA was run on ERPs of the preparation interval (on 500 time points = 1000 ms CSI) including the conditions switch-

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[8] The relevant and irrelevant attributes for each task could not be submitted into one PCA because ERP trial numbers did not allow a further sub-segmentation by another condition.

repeat and task. PCAs were performed on the covariance matrices and their solutions were Varimax-rotated to yield uncorrelated temporal components; the criterion for component extraction was that of eigenvalue ≥1; only components accounting for at least 2% of the variance were subjected to statistical analyses. To identify components sensitive to experimental manipulations ANOVAs were run on the scores of the PCA components, which represent the amplitude of components at each electrode for each condition and subject. To assess potential interactions of the experimental conditions with scalp regions minimizing the number of levels of that factor, amplitudes were averaged for groups of electrodes along the anterior-posterior (4 levels) and laterality (3 levels) dimensions; region and laterality were factors in the ANOVA. Significance levels were adjusted using the Huynh-Feldt correction for violations of sphericity (but unadjusted degrees of freedom are reported).

RESULTS

Behavioural data

Mean correct RTs and error rates for the combinations of switch/repeat, task, CSI, expression and letter type are given in Table 4.1 for the face task and Table 4.2 for the letter task (see also Figure 4.2). Trials following errors and trials with RTs below 200 ms or 3000 ms were excluded from the analysis. An ANOVA was run including the factors CSI (200 ms, 1000 ms), task (face, letter), switch (switch, repeat), expression (emotional, neutral) and letter type (vowel, consonant). It has to be noted here that all participants responded to emotional faces and vowels with the left arrow key and to neutral faces and consonants with the right arrow key. As a result any interaction of face expression and letter type is very likely to reflect the effect of congruency (e.g., emotional-vowel= congruent, emotional-consonant= incongruent).

Responses were slower for switch (805 ms) than for repeat (742 ms) trials, $F(1, 19) =$ 66.11; $p < 0.001$, slower for the short (832 ms) than for the long CSI (715 ms), $F(1, 19) =$ 111.95; $p < 0.001$, and slower in the face task (785 ms) than in the letter task (762 ms), $F(1, 19) = 17.73$; $p < 0.001$. Switch cost was reliably reduced from 77 ms in the short CSI to 50 ms in the long CSI, $F(1, 19) = 9.8$; $p < 0.01$. In the face task responses were faster to emotional (769 ms) than neutral (805 ms) faces while in the letter task they were faster to neutral (743 ms) than emotional faces (780 ms) [task by expression, $F(1, 19) = 37.36$;

$p < 0.001$]. Expression also interacted with letter type, reflecting the congruency effect with faster responses for congruent (759 ms) than incongruent (788 ms) trials, $F(1, 19) = 34.26$; $p < 0.001$. There were further three-way interactions between switch, task and CSI, $F(1, 19) = 6.03$; $p < 0.05$, switch, expression and letter type (switch by congruency), $F(1, 19) = 6.56$; $p < 0.05$; and a four-way interaction between switch, CSI, expression and letter type $F(1, 19) = 6.16$; $p < 0.05$.
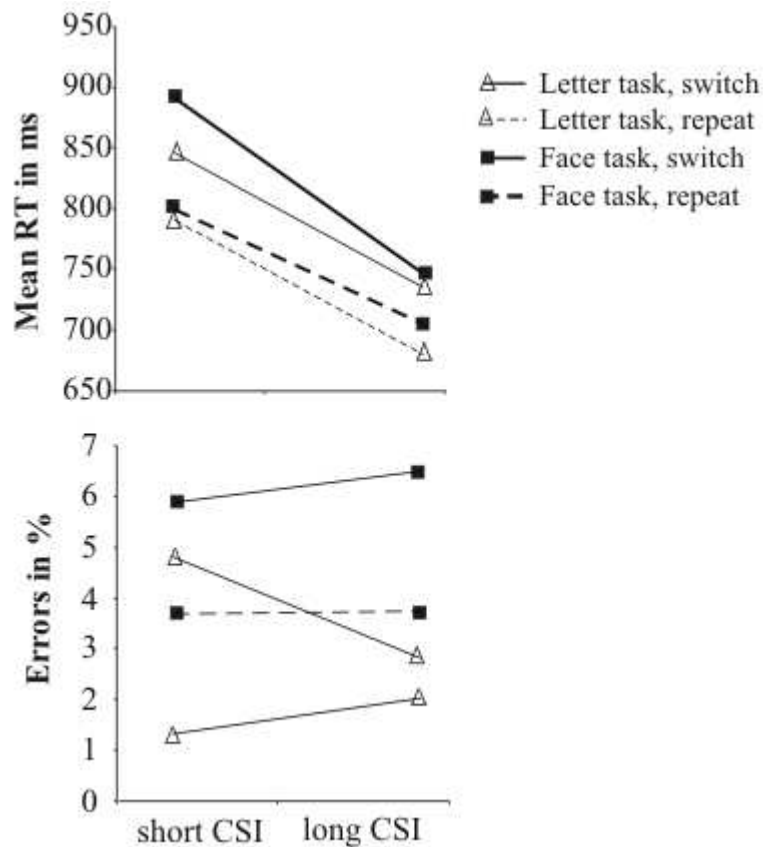
Figure 4.2 *RTs and error rates by switch, task and CSI*

Separate analyses for the two tasks show in the *face task* an overall switch cost of 69 ms, $F(1, 19) = 60.33$; $p < 0.001$, which reduces reliably from 95 ms in the short CSI to 43 ms in the long CSI (switch by CSI, $F(1, 19) = 13.13$; $p < 0.01$). Responses were faster for emotional faces (769 ms) than neutral faces (801 ms), $F(1, 19) = 7.14$; $p < 0.05$, and faster for congruent (765 ms) than incongruent (806 ms) trials, $F(1, 19) = 35.68$; $p < 0.001$. The congruency effect was reduced from 57 ms in the short to 25 ms in the long CSI, $F(1, 19) = 5.52$; $p < 0.05$. Switch cost in the *letter task* was 58 ms, $F(1, 19) = 31.19$; $p < 0.001$; and responses were faster for neutral (743 ms) than emotional faces (780 ms), $F(1, 19) = 39.1$; p

< 0.001. Congruent trials were responded to faster (753 ms) than incongruent trials (770 ms), $F(1, 19) = 6.94$; $p < 0.05$ and this congruency effect was larger for switch (32 ms) than repeat (1 ms) trials, $F(1, 19) = 7.93$; $p < 0.05$. On switch trials there was a marginally reliable reduction in congruency effect from the short (50 ms) to the long CSI (13 ms), $F(1, 19) = 3.34$; $p = 0.08$, while on repeat trials the effect shows the opposite pattern (congruency effect short CSI -10 ms vs. long CSI 11 ms, difference n.s.), [switch by CSI by congruency, $F(1, 19) = 5.61$, $p < 0.05$].

There were more errors on switch (4.9%) than repeat (2.6%) trials, $F(1, 19) = 40.14$; $p < 0.001$; in the face task (4.9%) than in the letter task (2.6%), $F(1, 19) = 17.06$; $p < 0.01$ and for emotional (4.3%) compared to neutral (3.1%) faces, $F(1, 19) = 9.27$; $p < 0.01$. There was also a highly reliable effect of congruency (expression by letter type interaction) with more errors for incongruent (5.4%) than congruent (2%) trials, $F(1, 19) = 38.85$; $p < 0.001$. The congruency effect was larger for switch (5.6%) than repeat (1.3%) trials, $F(1, 19) = 44.00$; $p < 0.001$, and larger in the face task (4.2%) than the letter task (2.7%), $F(1, 19) = 5.24$; $p < 0.05$. The three-way interaction between switch, CSI and task approached significance $F(1, 19) = 2.94$; $p = 0.1$.

Separate analyses for the two tasks showed for the *face task*: a switch cost of 2.5% (switch, 6.1%, repeat 3.6%, $F(1, 19) = 19.86$; $p < 0.001$), more errors for emotional (5.9%) than neutral (3.8%) faces, $F(1, 19) = 8.15$; $p < 0.05$, a congruency effect with more errors for incongruent (7%) than congruent (2.7%) trials and an interaction between switch and congruency with a larger congruency effect for switch (6.7%) than repeat (1.8%) trials, $F(1, 19) = 21.1$; $p < 0.001$. For the *letter task* there was an overall switch cost of 2.1% (switch, 3.6%, repeat 1.6%, $F(1, 19) = 20.31$; $p < 0.001$), which was reliably reduced from 3.3% in the short CSI to 0.8% in the long CSI, (switch by CSI, $F(1, 19) = 6.17$; $p < 0.05$. There was further a congruency effect of 2.7%, $F(1, 19) = 26.14$; $p < 0.001$, which was larger for switch (3.4%) than repeat (2%) trials, $F(1, 19) = 22.35$; $p < 0.001$.

To sum up, reliable switch costs were observed in both tasks as were reliable effects of facial expression. In the face task, participants were faster responding to emotional than neutral faces (although making more errors) while in the letter task the opposite was found suggesting that when the emotional expression was irrelevant to the task a fearful/angry

face was harder to ignore than a neutral one. Switch costs reduced reliably in both tasks from the short compared to the long CSI in either RT (for the face task) or errors (for the letter task), which suggests that participants used the longer interval for task-set preparation. This is further supported by a reduction in the RT effect of congruence with preparation in the face task. For the letter task, this reduction was limited to switch trials, for some reason. For both tasks' error rates and letter task RTs congruence effects were larger on switch than repeat trials.

Face task: long CSI post-stimulus ERPs

Effects of switching and emotional expression on latency and amplitude. Figure 4.3 shows waveforms for emotional and neutral faces separately for switch and repeat.
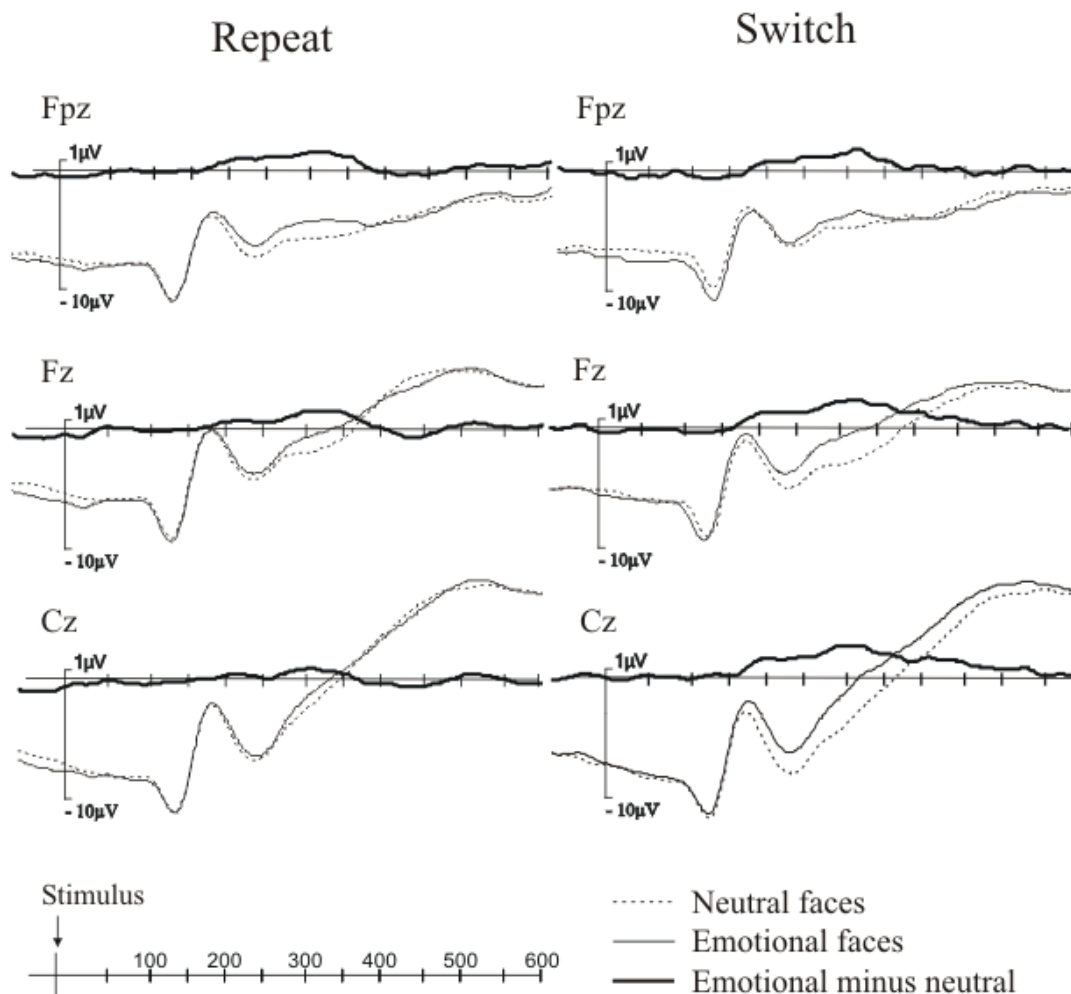
Figure 4.3 *Waveforms and difference waves for emotional and neutral faces for switch and repeat trials (face task)*

Figure 4.4 shows the emotional minus neutral difference waves in those electrodes and in global field power (GFP). The GFP difference waves show that there is an EEE with a latency of about 150 ms, and that there is no suggestion of any difference in the effect's latency between switch and repeat trials.
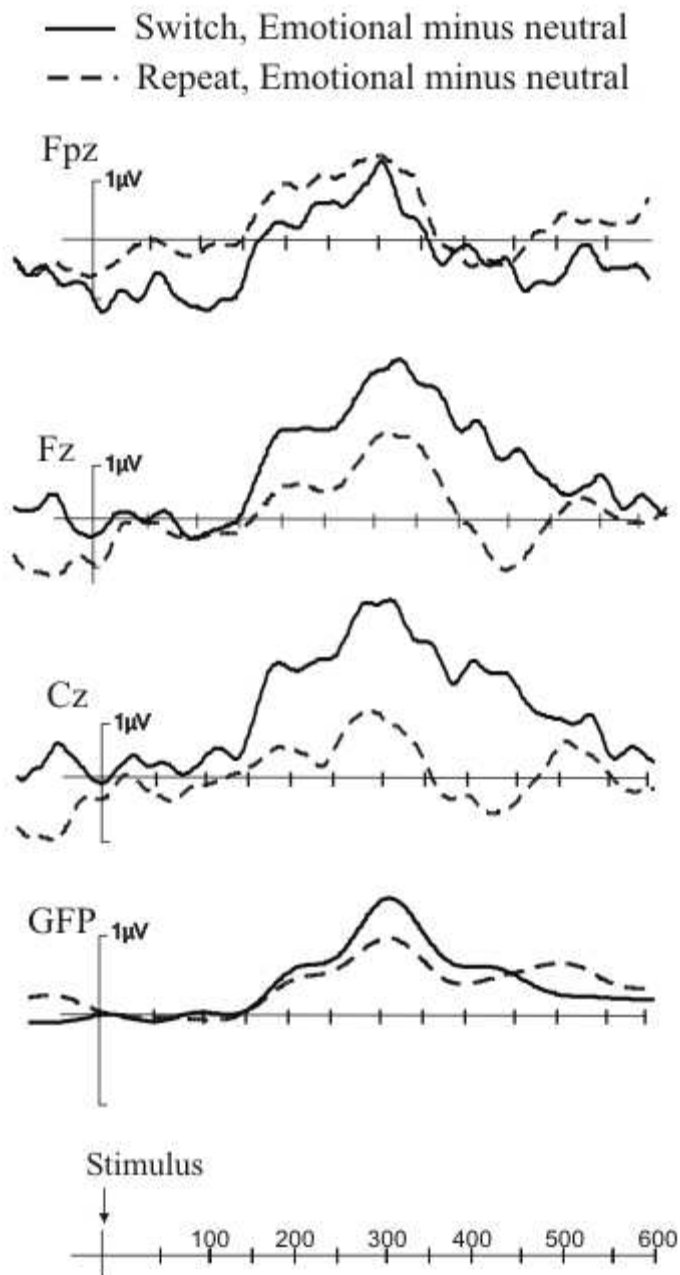
Figure 4.4 *Difference waves for emotional minus neutral faces for switch and repeat trials (face task)*

For switch trials the effect rises to a greater peak amplitude reflecting a larger difference in activity (power) between emotional and neutral faces on switch trials. This peak is reached at approximately the same latency for switch and repeat trials. Given these results a quantitative comparison of the latencies was not carried out.

PCA on the post-stimulus ERPs of the face task identified five components that accounted for at least 2% of the variance; all were sensitive to switching and/or emotional expression (see Figure 4.5 for components and their topography and Table 4.3 for statistics). As in the PCAs of our previous experiments the first component captured an overspill of the preparation related switch positivity into the stimulus interval. Its loadings were highest at ~110 ms, after which they decreased rapidly, but from about 200 ms on (until ~400 ms) a second, more gradual rise can be observed. This component was also
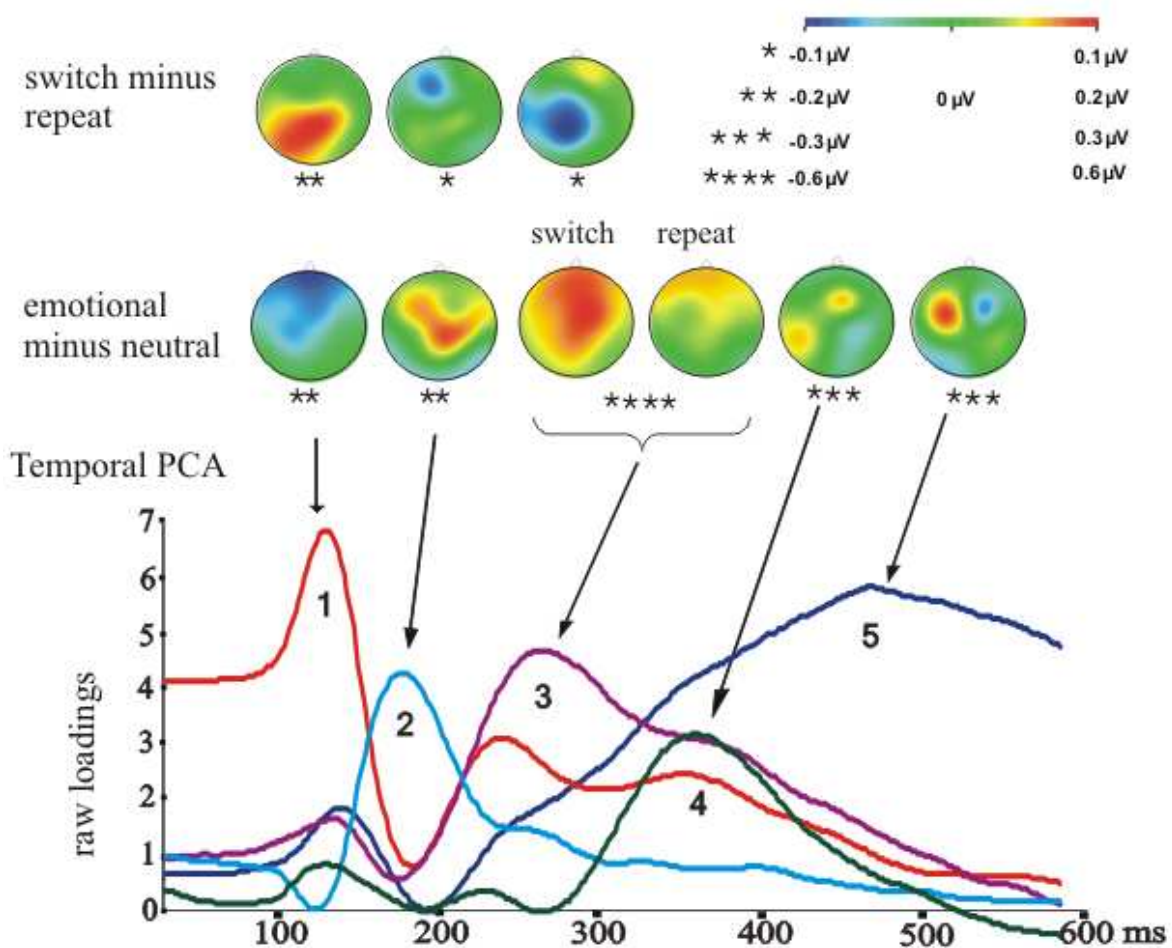
Figure 4.5 *PCA components and their topographies for the face task (switch by emotion)*

sensitive to face expression; however, due to its bimodal shape we hesitate to interpret this as a very early face expression effect. The second component, peaking at ~160 ms was also sensitive to switching and emotional expression. Here amplitudes were more negative for switch than repeat in left fronto-central regions; for emotional faces amplitudes were more positive than for neutral faces in central and parietal regions of the scalp. The following component (3) with high loadings between 210 and 320 ms seems to capture both the post-stimulus switch negativity seen in previous studies (e.g., Karayanidis et al., 2003; Lavric et al., 2008) and the emotion expression effect reported by Eimer et al., 2002. Here, switch interacted with facial expression, region and laterality pointing to topographical differences of the EEE between switch and repeat trials. Interestingly, the effect (more positive amplitudes for emotional vs. neutral faces) was larger and covered wider regions of the scalp on switch than on repeat trials. In fact, switch trials show more the typical topography reported by Eimer et al. On repeat trials, the positivity was more confined to anterior regions of the scalp. The following component (4) explained only 5% of the variance and showed an interaction between expression, region and laterality with more positive amplitudes for emotional (vs. neutral) faces in central and left parietal regions. The component (5) explaining most of the variance (40%) with high loadings from ~320 ms until the end of the interval showed sensitivity to facial expression. The topography of the difference - a larger positivity for emotional vs. neutral over central areas of the scalp-suggests that it reflects activity over the motor cortex since emotional and neutral faces were associated with the left and right hand responses respectively.

To sum up, the typical ERP effects of switching were observed: an intrusion of the preparation-related positivity into the post-stimulus interval and a post-stimulus switch negativity in the 200-300 ms range. PCA found two components in the time range where Eimer et al. observed the EEE: one captures a central/parietal positivity for emotional vs. neutral faces starting to rise at ~120 ms (peaking at ~160 ms); its onset coincides with that found by Eimer et al., its topography is slightly more posterior. The other component with high loadings between 200 and 300 ms captures the EEE with its typical topography. The effect is larger and more widespread on switch trials while on repeat trials it showed a more anterior distribution.

Effects of letter type (vowel-consonant) on face task amplitudes. Letter type was found to affect ERP waveforms in the letter task throughout the whole post-stimulus interval (as described below). To examine whether similar modulations could be detected in the face task, where letter type was the irrelevant dimension, the following PCA was run. ERPs of vowel and consonant trials (and their difference waves) are shown separately for switch and repeat in electrodes Fz, Cz and Pz are shown in Figure 4.6. PCA on post-stimulus ERPs with the conditions switch-repeat and letter type identified five components that explained more than 2% of the variance; four of those were sensitive to switching and/or letter type (shown in Figure 4.7, for statistics see Table 4.4). As the effects of switching on face task ERPs were already described above the following description includes only effects of letter type and their possible interactions with switching.
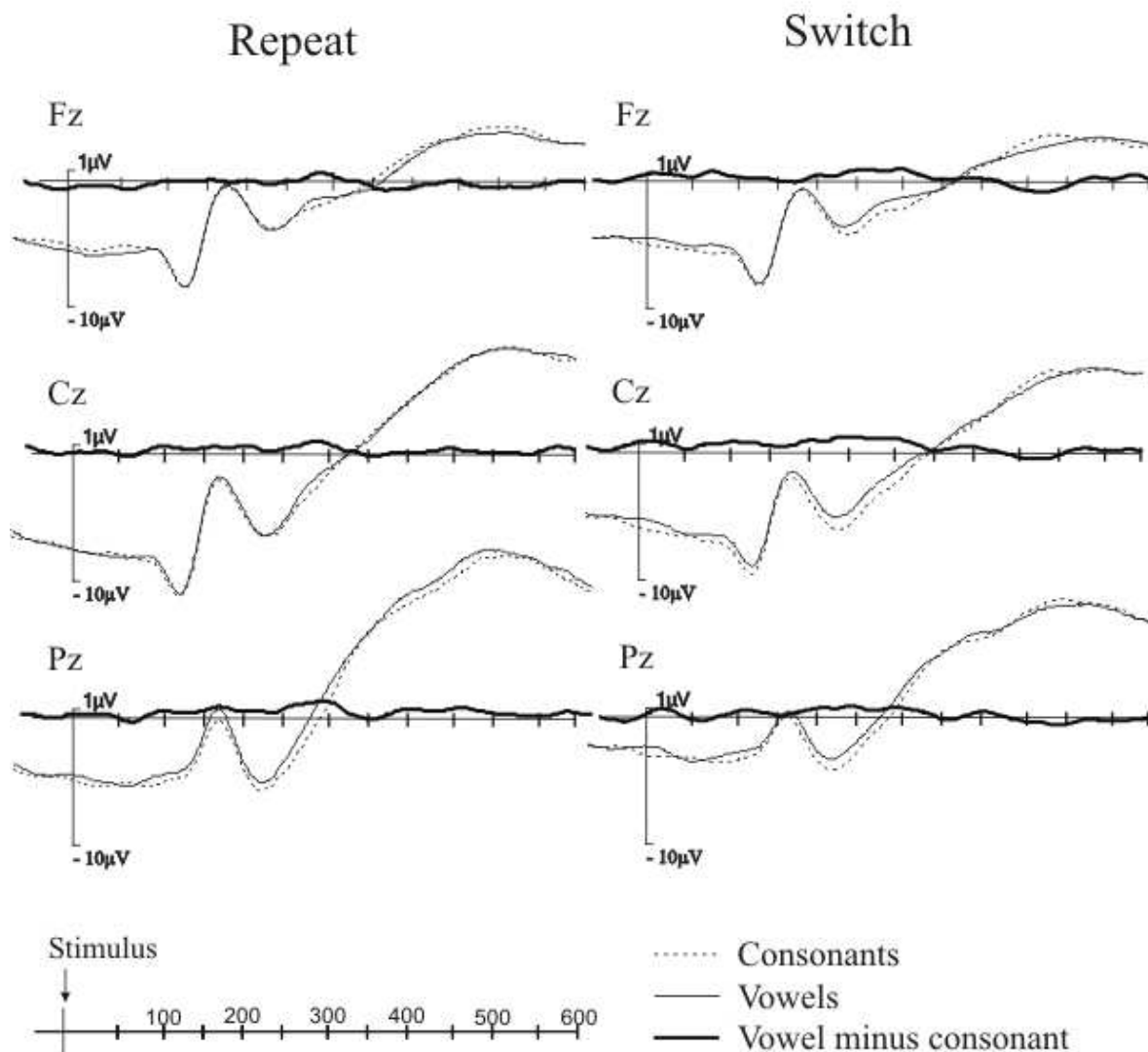
Figure 4.6 *Waveforms for vowels and consonants and their difference waves (face task)*
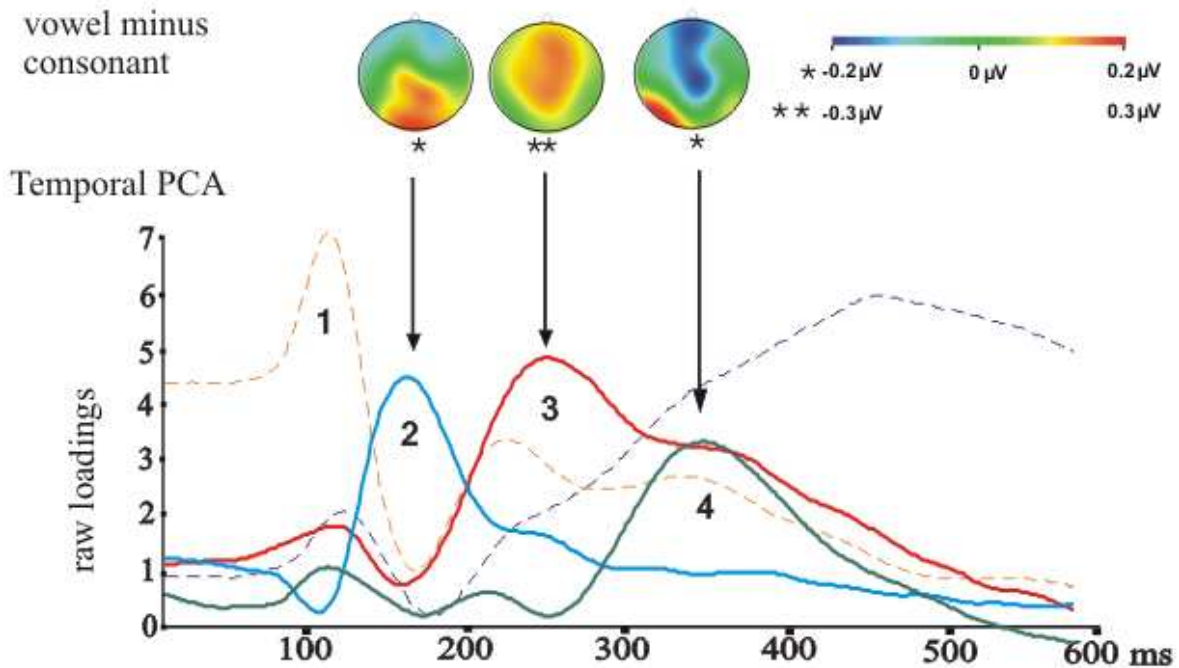
Figure 4.7 *PCA components and their topographies for the face task (switch by letter type)*

First effects of letter type were detected early, captured by the component (2) peaking at ~160 ms. Amplitudes for vowels were more positive than for consonants in posterior regions due to a larger N1 (i.e., more negative amplitudes) for consonants. The following component (3), with high loadings between 210 and 320 ms also showed sensitivity to letter type. Here, amplitudes were more positive for vowels than consonants over widespread, central regions of the scalp. The next component (4), peaking at ~350 ms showed letter type differences expressed in more negative amplitudes for vowels than consonants in midline regions and more positive amplitudes for vowels in left posterior regions.

In summary, the irrelevant dimension letter type affected face task ERPs from about 140 ms to about 400 ms post-stimulus. Although visual inspection of the waveforms (Figure 4.6) seems to show that letter type differences are somewhat larger on switch than repeat trials this interaction did not reach significance for any component in the PCA analysis.

Letter task: long CSI post-stimulus ERPs

Effects of switching and letter type on letter task amplitudes. Figure 4.8 shows waveforms for vowels and consonants separately for switch and repeat trials in electrodes Fz, Cz and Pz. Figure 4.9 shows the vowel minus consonant difference waves in those electrodes and in global field power (GFP). The GFP difference wave shows a steep rise for repeat trials from about 300 ms onwards; at this stage the waveform for switch trials rises only slightly reaching amplitudes (~ 350 ms) that are considerably smaller than those for repeats. From about 430 ms onwards GFP starts to increase more rapidly for switch trials, reaching its highest amplitudes towards the end of the interval (~600 ms). Although at the earlier stage
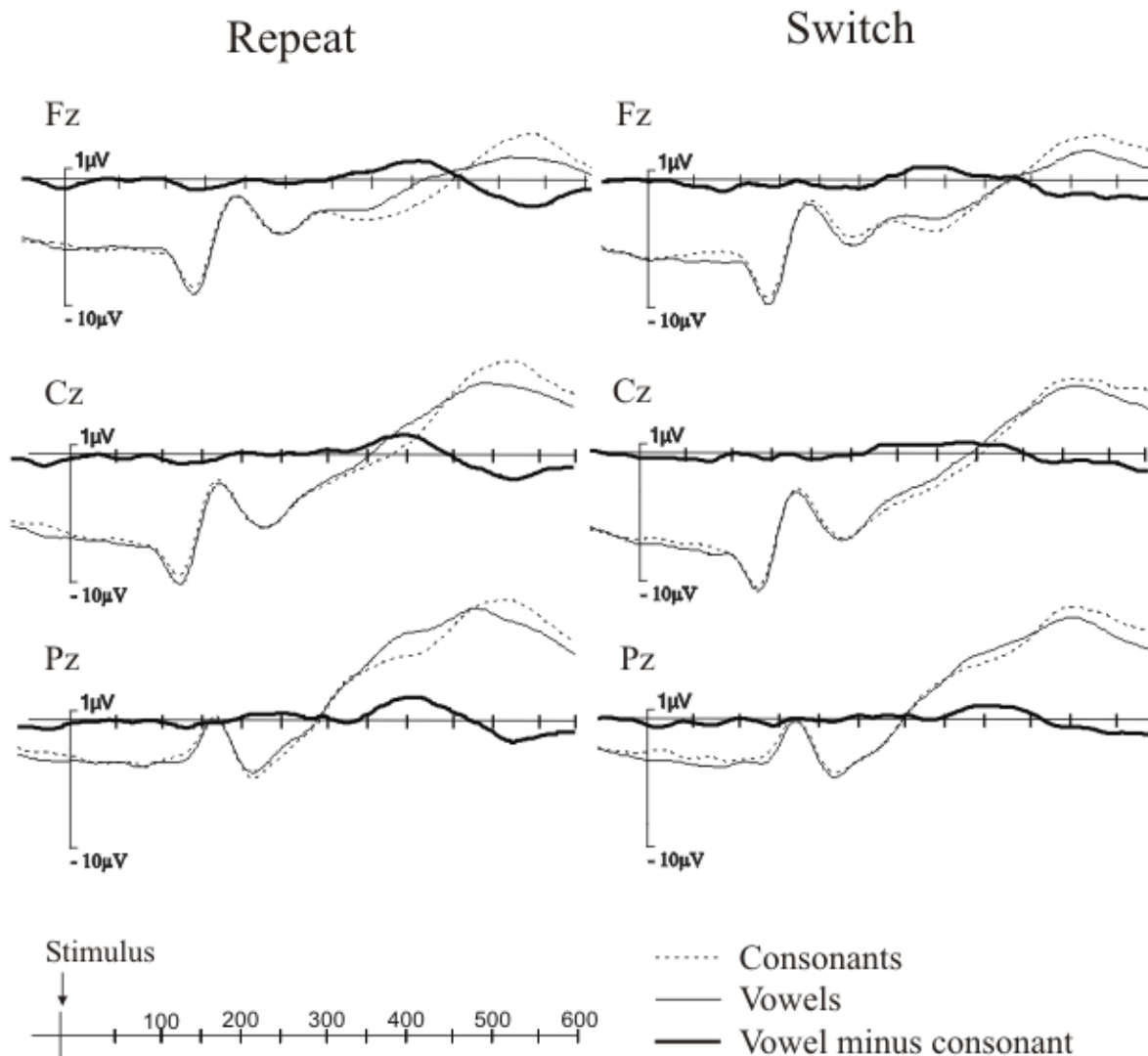
Figure 4.8 *Waveforms for vowels and consonants and their difference waves (letter task)*
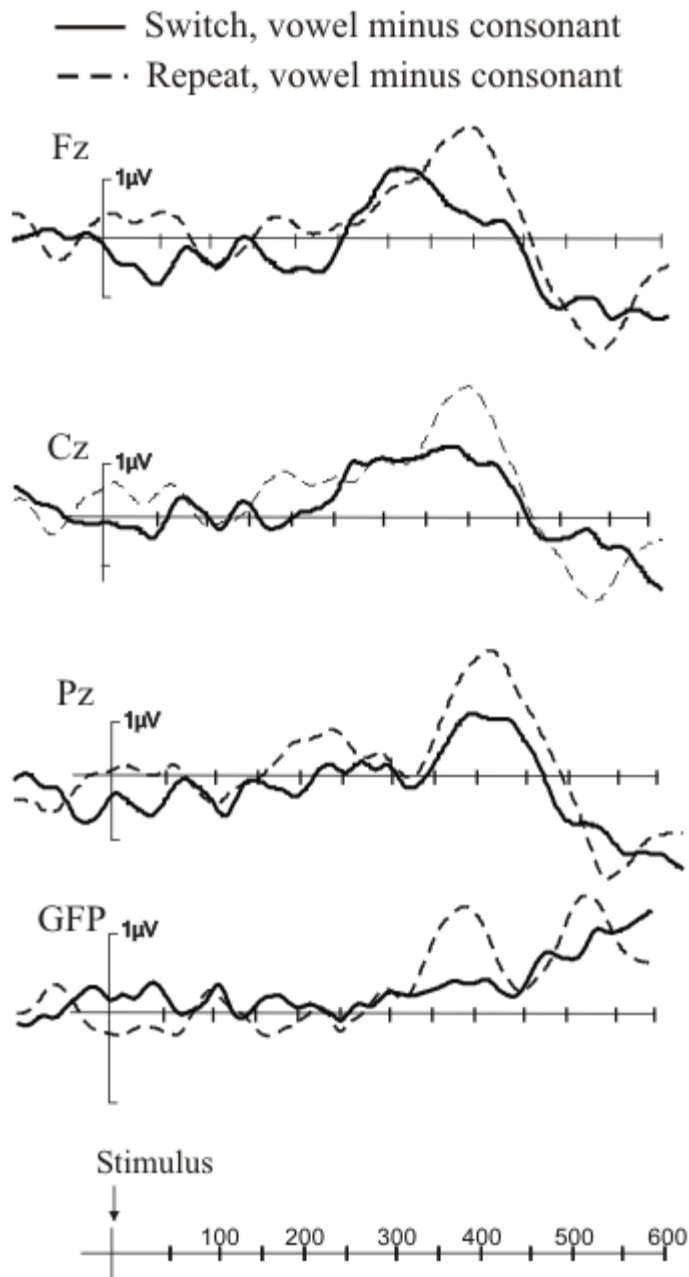
Figure 4.9 *Difference waves for vowels minus consonants for switch and repeat trials (letter task)*

there are sizeable differences in amplitudes of GFP difference waves for switch and repeat trials, waveforms do seem to start rising around the same time (only for switch trials this rise is very subtle). Given this pattern of results a statistical comparison of latencies did not seem justified. PCA on post-stimulus ERPs with the conditions switch-repeat and vowel-

consonant identified five components that explained more than 2% of the variance, all sensitive to switching and/or letter type (shown in Figure 4.10, for statistics see Table 4.5).

Similar to results in the PCA on face task ERPs, switching affected amplitudes throughout the whole post-stimulus interval starting with the overlap of the posterior switch positivity (here with a concurrent frontal negativity). Between 140-200 ms amplitudes in occipital regions were also more positive for switch than repeat trials (now with a concurrent central negativity). This, however, does not appear to be a continuation of the previous effect. Rather, it was caused by more negative amplitudes for repeat trials (a larger N1) particularly in left occipital regions together with slightly more positive amplitudes
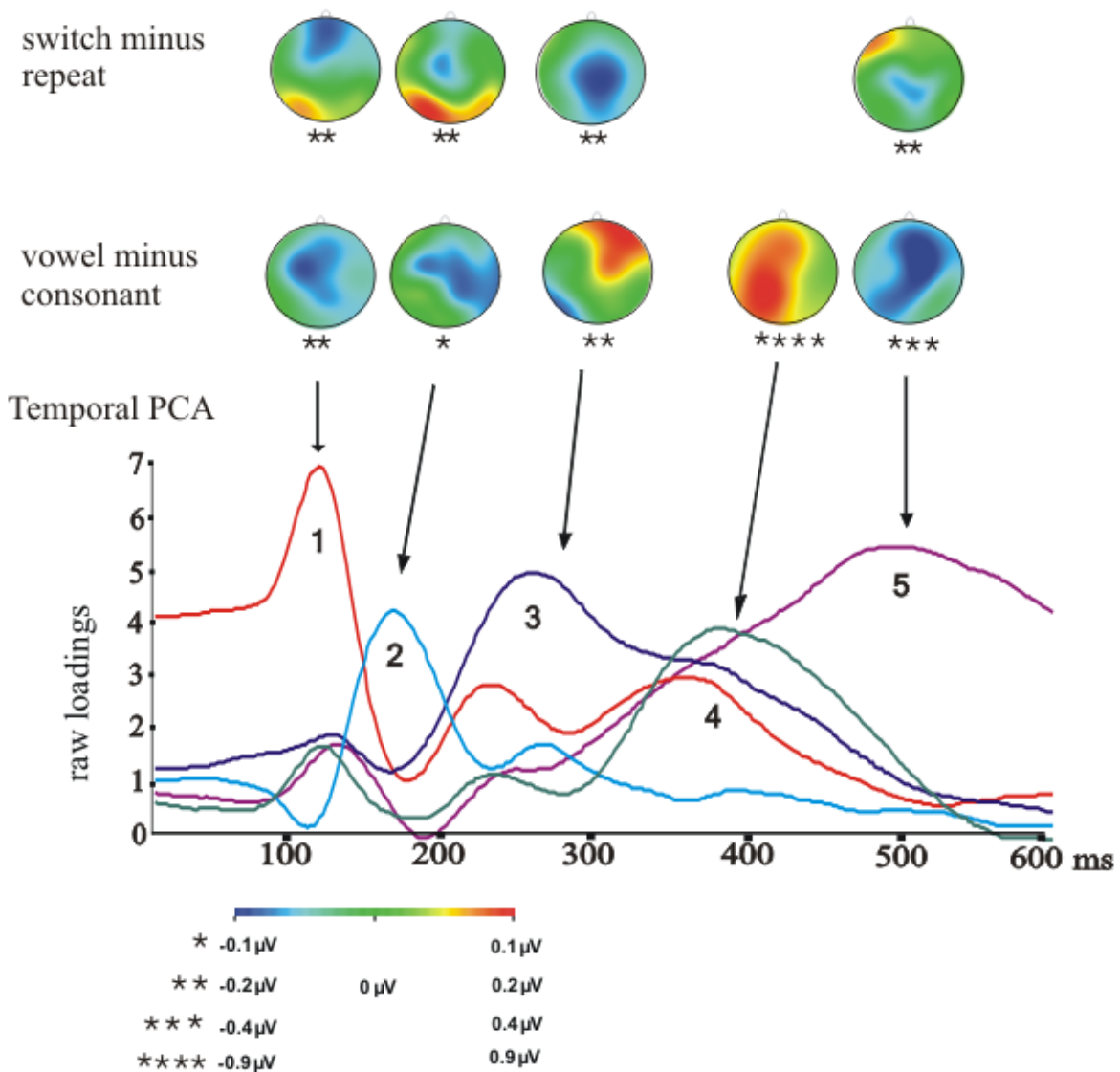
Figure 4.10 *PCA components and their topographies for the letter task (switch by letter type)*

centrally. From about 200 ms onwards the post-stimulus switch negativity emerged (captured in components 3 and 5) and continued until the end of the interval. Apart from an early, somewhat ambiguous effects of letter type (as captured by component 1 with its bimodal distribution), component 2 (between 140-200 ms) was also sensitive to differences between vowels and consonants. Amplitudes were more negative for vowels than consonants in central regions. Between 200 and 320 ms amplitudes were more negative for vowels than consonants in left occipital regions concurrent with a right frontal positivity. This could reflect a larger selection negativity for vowels with a concurrent frontal selection positivity. Between 320 and 400 ms amplitudes were more positive for vowels in most (apart from right parietal/occipital) regions of the scalp while in the following window (from 400 ms onwards until the end of the interval) amplitudes for vowels were more negative. This pattern seems due to an earlier rise of the P3 for vowels, whilst the P3 for consonants started increasing in amplitude when the P3 for vowels was already declining.

To sum up, as in the face task, switching affected amplitudes of the letter task in the typical way. Letter type affected amplitudes throughout the whole post-stimulus interval. We are not aware of any previous reports of effects of letter type in the literature. Although vowel consonant differences appear to be larger on repeat than switch trials when visually inspected (see Figure 4.8), particularly in the range between 250-350 ms, the interaction between the two variables failed to reach significance (component 5, switch x letter type x laterality, $p = 0.077$, see table 4). While later differences between the letter types could be due to the fact that they were responded to with different hands early effects are more likely due to differences in perceptual properties or differences in the speed of recognition.

Effects of facial expression on letter task amplitudes. ERPs of emotional and neutral face trials (and their difference waves) are shown separately for switch and repeat trials in Figure 4.11. In this task the emotional expression of the face was the irrelevant dimension. PCA on post-stimulus ERPs including the conditions switch-repeat and emotional-neutral identified five components that explained more than 2% of the variance, four of those were sensitive to switching and/or letter type (shown in Figure 4.12, for statistics see Table 4.6). Since the effects of switching on letter task ERPs have already been described above, this analysis focuses on effects of emotional expression and their possible interactions with switching.
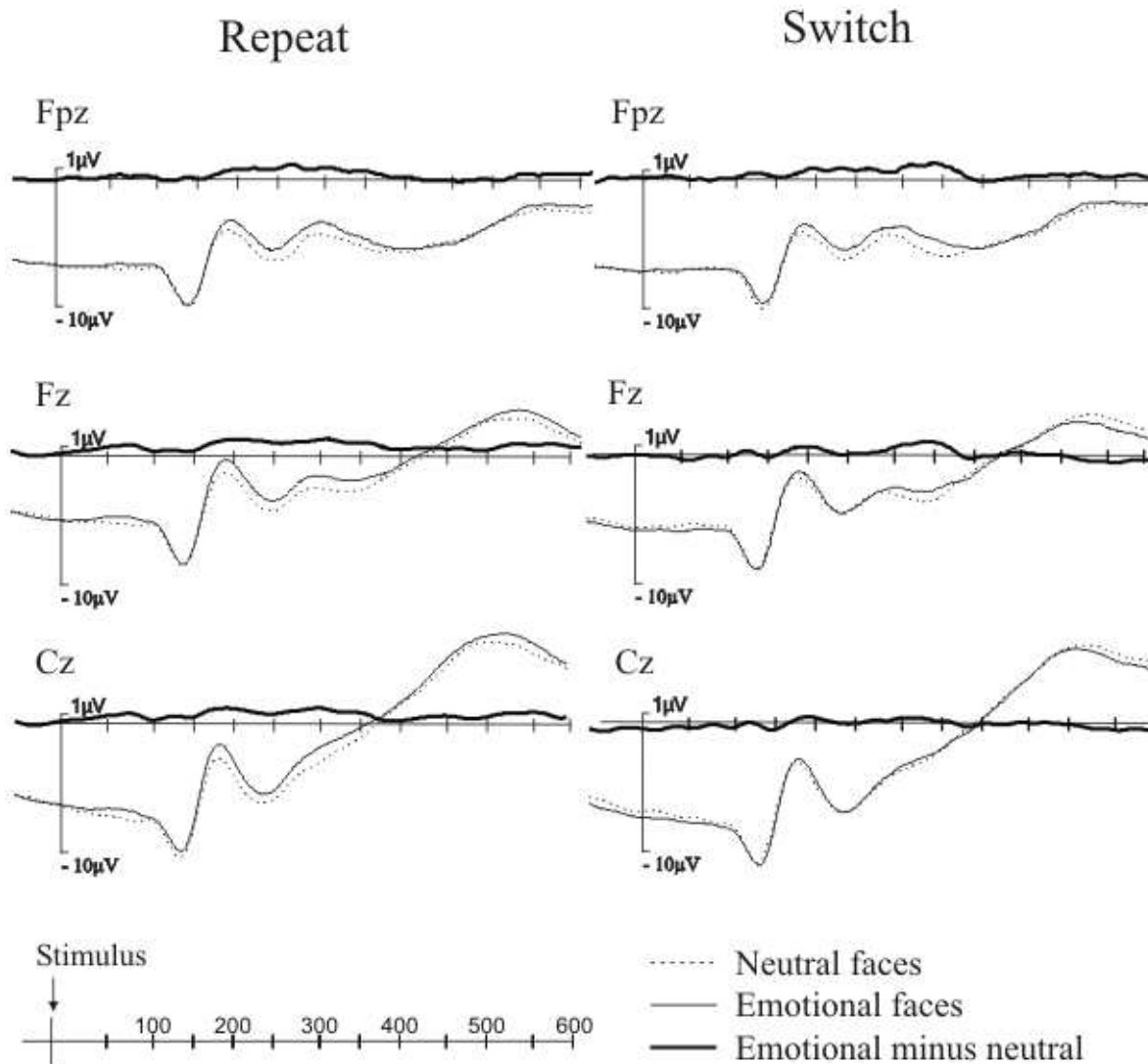
Figure 4.11 *Waveforms and difference waves for emotional and neutral faces for switch and repeat trials (letter task)*

As in the PCA on face task ERPs, the EEE as described by Eimer et al. seems to be captured by two PCA components, the first rising at ~120 ms with a peak at ~160 ms showing a widespread (central) positivity for emotional versus neutral faces. In the second component, with high loadings between ~200- 350 ms the emotion effect has a similarly central but slightly more anterior distribution. From about ~350 ms onwards until the end of the interval amplitudes are more positive for emotional than neutral faces in posterior regions due to a larger P3 for the former.

To summarise, although not relevant for the letter task, the facial expression affected ERPs from about 120 ms onwards throughout the whole post-stimulus interval. There were no reliable modulations of these effects by switching.
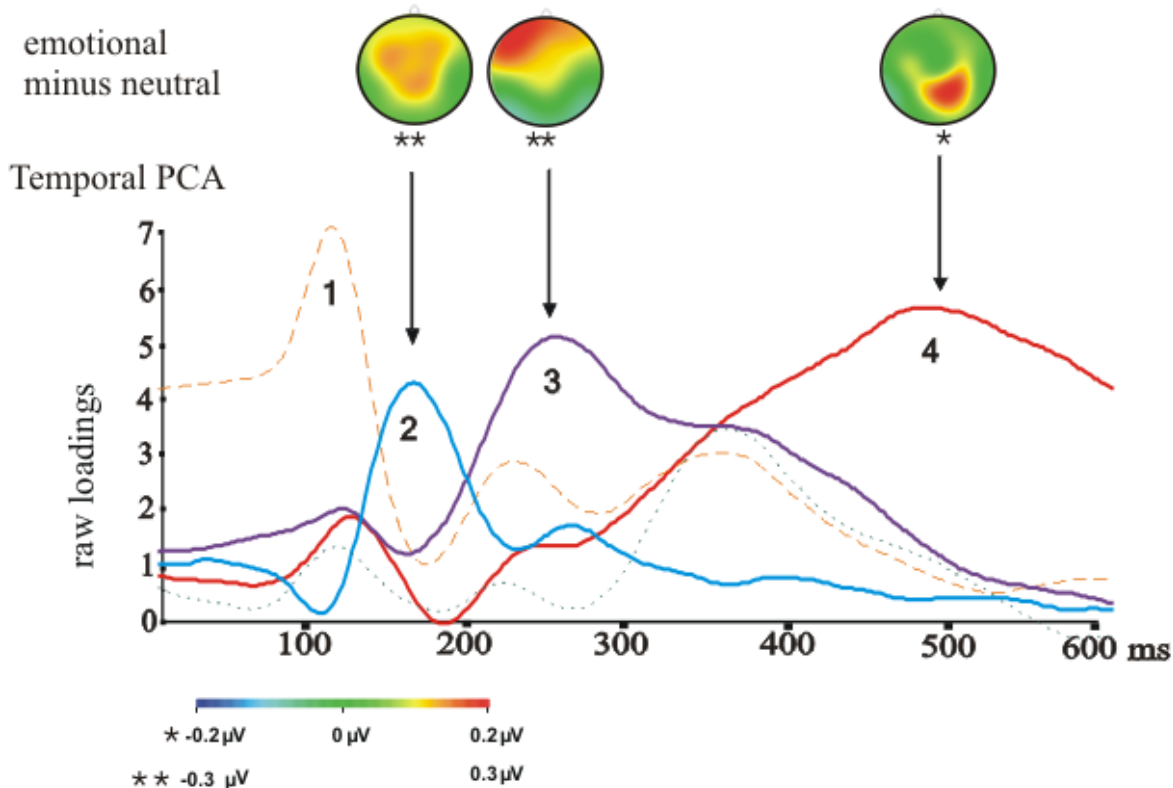
Figure 4.12 *PCA components and their topographies for the letter task (switch by emotional expression)*

Long CSI, Cue interval

ERPs for switch and repeat trials, separate for the two tasks are shown in Figure 4.13. PCA on ERPs of the long CSI with the conditions switch-repeat and task identified five components that accounted for at least 2% of the variance; all of which were sensitive to switching (see Figure 4.14 for components and their topographies, and Table 4.7 for statistics). As the cue interval was not the focus of this study, these results will only be described very briefly as evidence of pre-stimulus preparation. The first two PCA components seem to capture sensory ERPs with small, local differences between switch and repeat. Component 3, peaking ~220 ms seems to occur in the same time window where we have previously seen an early positivity for switch (Experiments 1 and 2, and Lavric et
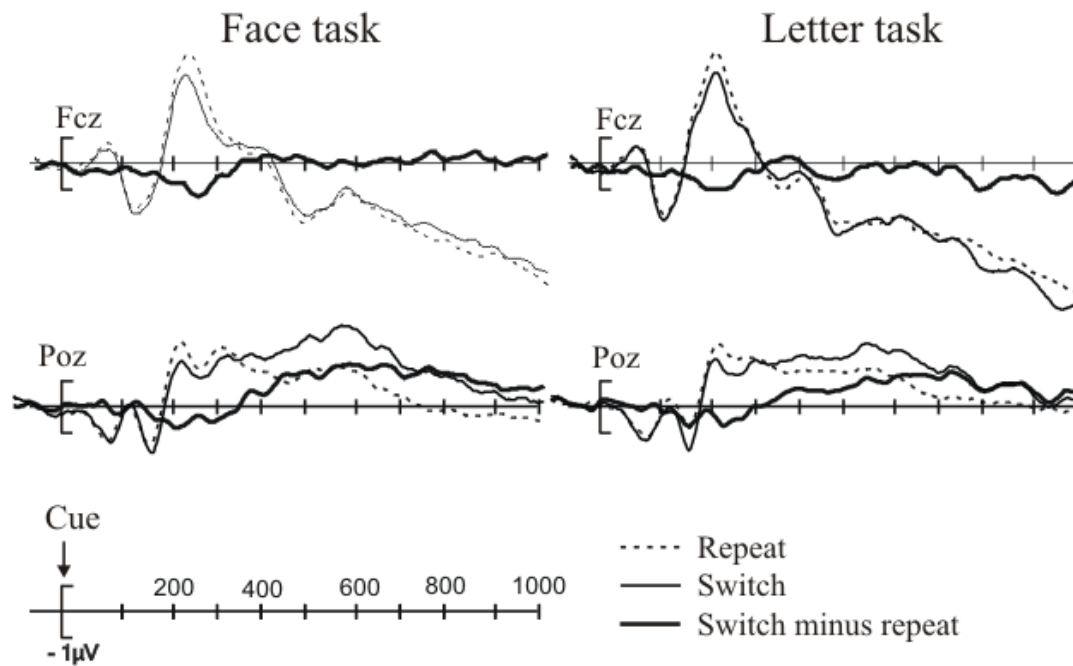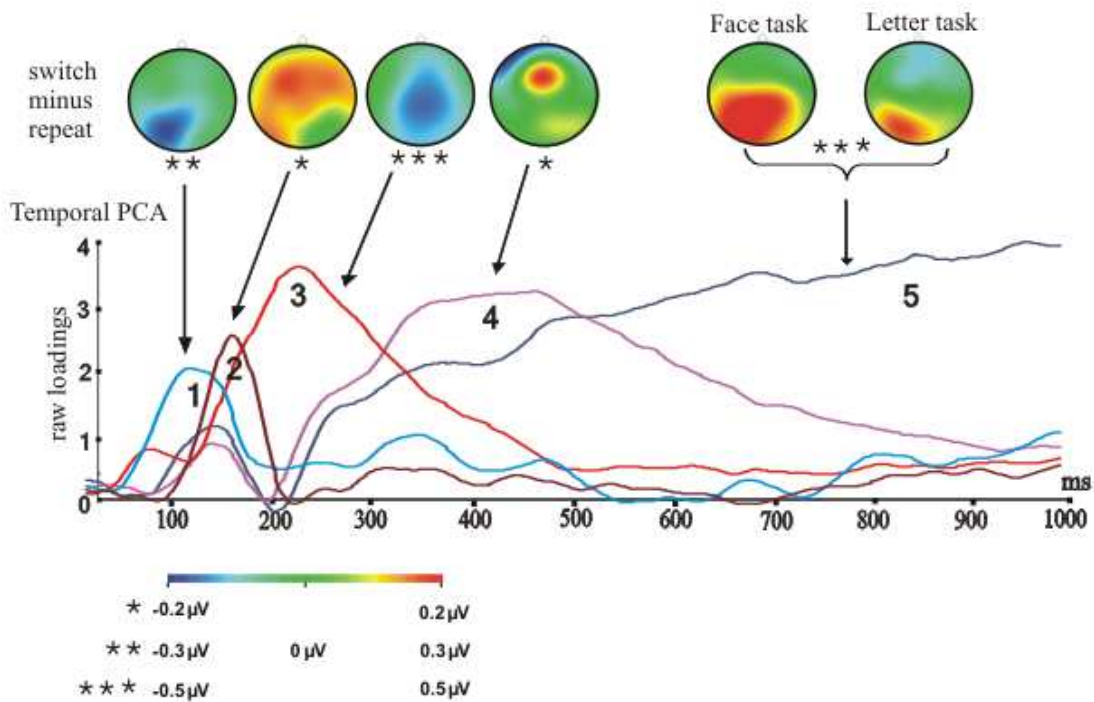
al, 2008), but here this positivity was larger for repeat trials resulting in a switch negativity. It is possible that the use of auditory rather than visual cues (as used in the previous studies), is responsible for this reversal. Another unpublished study from our lab using auditory cues, has shown the same pattern as observed here. This might have interesting implications for what this early switch-repeat difference reflects but it will not be discussed here further. The most important component for the purposes of this investigation is the one explaining nearly 50% of the variance, starting to rise ~ 300 ms and with high loadings until the end of the cue interval. It captures the posterior switch positivity, and in the letter task it is accompanied by a frontal negativity. Previous studies (Lavric et al., 2008; Elchlepp et al., 2011; Karayanidis et al., 2011) have provided evidence that this positivity is a marker of successful preparation for a switch. Together with the behavioural RISC effect it supports our assumption that participants were using the cue interval to prepare for a task switch.

DISCUSSION

The aim of this study was to investigate the locus of modulations of the ERP waveform induced by prepared switches between a face expression discrimination and a vowel-consonant classification performed on a compound stimulus consisting of a face with a letter superimposed. Reductions in behavioural switch costs and congruence effects between the 200 ms and 1000 ms CSI suggest that participants were using the longer CSI for effective task-set preparation; pre-stimulus ERPs also showed the late positivity as a signature of task-set preparation.

In both tasks we found reliable RT differences depending on facial expression; in the face task responses were 36 ms faster for emotional than neutral faces although accompanied by 2% more errors for the former. It seems that fearful or angry faces attract attention to the face dimension, possibly increase arousal, which might be expressed in fast but sometimes wrong responses. Results in the letter task confirm this; here responses for emotional faces were slower suggesting it was harder to ignore these expressions and focus on the letter. This interference appears fairly automatic since it was not modulated by whether participants had done the face task on the previous trial or were repeating the letter task.

Analysis of post-stimulus ERPs from face task trials (from the long-CSI blocks) showed a pattern that was somewhat unexpected. An emotion expression effect, similar to that reported by Eimer and colleagues was apparent starting at ~ 120 ms. There was however no sign that the onset of this effect was modulated by whether participants were repeating the face task or had just switched to that task (see Figures 4.3 and 4.4). When the EEE reached its maximum (around 300 ms) it was considerably larger for switch than repeat trials. Also, on switch trials the effect showed its typical fronto-central topography although extended somewhat to more posterior regions. On repeat trials the effect was confined to more anterior rather than central regions. The lack of any delay in processing the facial expression on switch trials seems to narrow down the alternatives of possible causes of the EEE. But before discussing this it is useful to look at what happened in the letter task, where the facial expression was irrelevant and where processing it was possibly even detrimental to performance. To recall, the experiments described in Chapter 2 found inertia of task activations of the irrelevant task (lexical processing in the non-lexical task) and they were greater when that task had just been performed on the previous trial. This study, however, found no modulation of irrelevant task activation by switching; here emotion expression effects were equally strong for both trial types. Seen in conjunction, the lack of a switch related delay of the EEE on face task trials, and the fact that the EEE on letter task trials is not amplified by a switch suggests it reflects an automatic process. This suggestion would be further strengthened if we found that the EEE is not modulated by which task is performed. Unfortunately, our PCA analyses do not allow this assessment. Therefore, a post-hoc analysis was run on ERP amplitudes comparing the EEE for face task trials with those of letter task trials. Two time windows were chosen to capture the early and late portions of the effect (150-250 ms, 250-350 ms) and time window was entered as a factor in the ANOVA. No reliable interactions involving emotional expression and task were found, not overall (task by emotion interaction, $F(1,19) = 0.001$; $p = 0.97$) nor in any of the regions or time windows, suggesting that the magnitude of the EEE is very similar in the two tasks. This allows the following interpretation. When spatial attention is oriented appropriately on the face (as in both tasks of this experiment) the emotional expression is registered fairly automatically. It is either not necessary that attention is directed to the facial features, or fearful and angry faces representing a strong, potentially dangerous social cue attract attention to those features once the face is presented in the fovea. On its own, the lack of any delay of the EEE when switching to the face task could also mean that there is

no "attentional inertia" and people are attending to the facial features to a similar extent on switch and repeat trials. The lack of a modulation of the EEE by task, however, makes the automatic registration account more likely. It is also in line with the behavioural findings that participants were faster responding to an emotional (than neutral) face in the face task but slower in the letter task when the face has an emotional expression. In the face task, it is possible that the emotion categorisation task exploits this automatic process, and hence the task can only be engaged/disengaged by modulating the connection between it and response selection.

At first glance the automatic registration version might seem at odds with the findings of Eimer et al. who observed an elimination of the EEE when faces were at unattended locations (Holmes et al., 2003) and an attenuation of the EEE when faces were presented in the fovea but lines to the left and right of it had to be attended (Eimer et al., 2003). The aspect in which our study differs from theirs is where spatial attention was directed to. It appears that once in the focus of spatial attention the registration of emotional content (or the formation of its representation in the neocortex) is fairly automatic. The study by Kiss & Eimer (2008) seems to confirm this. Here spatial attention was oriented to the face while participants made the emotion discrimination (fearful versus neutral) and although on some trials faces were only presented subliminally (8 ms) still a reliable EEE was observed. Consequently, if the emotion-processing indexed by the EEE reflects automatic activity in emotional circuitry epiphenomenal to the series of processes required to classify the emotion, then it was an unsuitable choice for asking where in this series delays occur on switch trials.

Some further questions that this current experiment raises are: why is the EEE larger on switch- than repeat face task trials and why does the topography of the effect differ for the two conditions. In this context one methodological flaw of this experiment needs to be mentioned; response keys for emotional and neutral faces were not counterbalanced across participants (as they were in Kiss & Eimer, 2008) meaning that an emotional face always required a left hand response while a neutral face always required a right hand response. That means the emotional minus neutral comparison in the ERP is also a comparison of left minus right hand responses. Particularly later in the ERP this motor activity becomes apparent as a negativity over the right motor cortex (activation) and a positivity over the

left motor cortex (deactivation; see component 5, Figure 4.5). RTs on repeat trials were relatively fast on long CSI face task trials (742 ms) and emotional faces (left key) were responded to 36 ms faster than neutral faces. That opens up the possibility that the right motor cortex might have already been activated and the left deactivated at quite an early stage (after ~300 ms) on some trials. The negativity in left posterior frontal regions might hence have diminished and distorted the EEE. If that was true this kind of distortion should be particularly evident on trials with fast (compared to trials with slow) responses. Indeed a post-hoc, visual comparison of these effects on fast and slow repeat trials confirmed this suspicion (see Figure 4.15). Although this can explain some of the topographic differences of the EEE between switch and repeat trials it does not explain why the effect is so much more anterior and smaller on slow repeat trials. This suggests that switch-repeat differences in the EEE are possibly caused by several factors. One of them is the overlapping motor activation on repeat trials at the later stage of the EEE (component 3, Figure 4.5). The early part of the EEE seems unaffected by this confound (component 2, Figure 4.5). Another factor could be that certain, more automatic neural generators (contributing to the central-parietal activations) are suppressed when the emotion judgment is made in a more task-dependent fashion recruiting more frontal regions of the cortex. The latter is in line with Eimer et al.'s suggestion that the EEE measured on the scalp has several underlying generators.

An ancillary aim of this experiment was to examine ERP differences between vowels and consonants. If this distinction modulates the ERP, then it would provide another potential measure of task-set inertia in the face task, and if the modulation is early, its latency could potentially index the locus of switching in the letter task. An effect of letter type was indeed observed in the ERP, and it spanned the whole of the post-stimulus interval analysed -- the first report of such an effect as far as we know. Although the difference emerged relatively early, its emergence in the difference wave was too noisy to permit a latency analysis in the letter task, and no reliable modulation of its amplitude by switching was found throughout the whole interval in the PCA analysis. Interestingly, letter type also affected amplitudes in the face task, also from about ~140 ms onwards, and by about the same amount on switch and repeat trials. That suggests that in both the face and the letter task the irrelevant dimension was processed unmodulated by whether the other task had just been performed or not. This seems to suggest that not only the perception of the emotional content of a face

but also perceiving the identity of a letter are processes that happen fairly automatically given appropriate orientation and distribution of spatial attention.
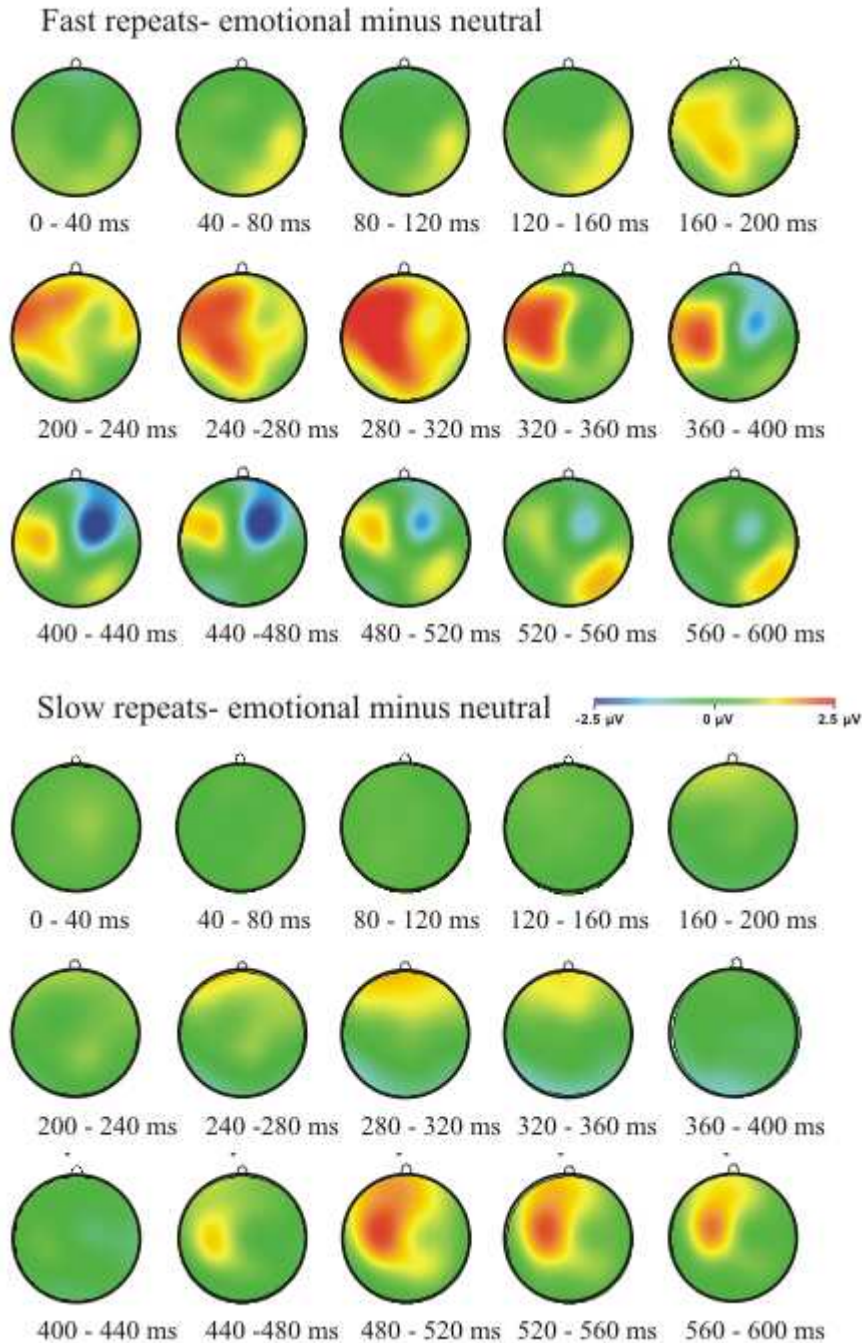
Figure 4.15 *Topographies of EEE on fast and slow repeat trials*

To sum up, the behaviour of the EEE in the ERP suggests that it indexes automatic activation of (possibly sub-cortical) emotion detection circuits (see Tamietto & de Gelder, 2010 for review) rather than an emotion categorisation process contributing to the emotion classification task. This renders it an unsuitable marker for localising the switch cost within task-specific processing. Its presence on switch and repeat trials in the letter task and the modulation of its amplitude by switching in the face task possibly relates to the extent to which deliberate processing overrides this automatic reaction. Of course, it remains a possibility that the EEE effect does localise the onset of a task-relevant emotion categorisation process exploiting the automatic detection of emotion, so that the only way to disengage the task is to disconnect response selection from this. Processing the identity of a letter seems to show a similar pattern; ERP differences between vowels and consonants in the letter task had an early onset which was not detectably delayed by switching. Polarity and topography of this modulation differed slightly between the letter and the face task, the latency of the vowel-consonant difference, however, appeared to start around the same time. Hence, in both tasks switching did not modulate the onset of processing the relevant or irrelevant task dimension, nor did it modulate the extent to which the irrelevant dimension was processed suggesting that face and letter features are processed fairly automatically.

Appendix Chapter 4: Data tables

Face task

		Short CSI				Long CSI			
		Emotional		Neutral		Emotional		Neutral	
		Vowel	Cons	Vowel	Cons	Vowel	Cons	Vowel	Cons
Switch	Mean RTs in ms (% errors)	861 (3.5)	907 (11.6)	946 (6.9)	862 (1.3)	714 (5.0)	743 (10.4)	773 (8.9)	752 (1.4)
Repeat	Mean RTs in ms (% errors)	754 (3.9)	804 (4.4)	842 (4.1)	796 (1.9)	672 (3.2)	697 (5.3)	733 (4.4)	708 (2.0)
Switch cost	Mean RTs in ms (% errors)	108 (-0.4)	102 (7.2)	104 (2.8)	67 (-0.6)	43 (1.8)	47 (5.1)	40 (4.6)	44 (-0.8)

Table 4.1 *RTs, error rates and switch costs for the face task*

Letter task

		Short CSI				Long CSI			
		Emotional		Neutral		Emotional		Neutral	
		Vowel	Cons	Vowel	Cons	Vowel	Cons	Vowel	Cons
Switch	Mean RTs in ms (% errors)	852 (2.8)	884 (7.1)	859 (7.5)	791 (0.6)	743 (1.8)	766 (3.8)	716 (5.1)	712 (0.3)
Repeat	Mean RTs in ms (% errors)	813 (0.7)	809 (2.6)	757 (1.0)	772 (0.6)	675 (2.3)	700 (1.3)	667 (3.1)	669 (1.0)
Switch cost	Mean RTs in ms (% errors)	39 (2.1)	75 (4.6)	102 (6.5)	19 (0.0)	68 (-0.5)	66 (2.5)	48 (2.7)	43 (-0.7)

Table 4.2 *RTs, error rates and switch costs for the letter task*

PCA Compo-nent	Variance accounted for	Peaking at/ High loadings between	Significant effects in ANOVA	df	F	p
1	25.1%	112 ms	switch x region expression x region switch x region x lat	3,57 3,57 6,114	3.60 4.77 3.02	< 0.05 < 0.05 < 0.05
2	6.8%	160 ms	expression x region switch x region x lat	3,57 6,114	3.59 3.01	< 0.05 < 0.05
3	17.2%	250 ms	expression expression x region expression x lat switch x lat switch x expression switch x exp x reg x lat switch only: expression expression x lat repeat only: expression expression x region expression x region x lat	1,19 3,57 2,38 2,38 1,19 6,114 1,19 2,38 1,19 3,57 6,114	14.79 11.12 5.20 4.33 3.79 3.89 13.15 3.59 5.48 9.67 3.71	< 0.01 < 0.01 < 0.05 < 0.05 0.067 < 0.01 < 0.01 < 0.05 < 0.05 < 0.01 < 0.01
4	5%	350 ms	expression x region x lat	6,114	5.44	< 0.01
5	40.3%	300 - 600 ms	expression x region x lat	6,114	10.97	< 0.001

Table 4.3 *PCA components of post-stimulus ERPs from the face task (by switch by emotional expression)*

PCA Compo-nent	Variance accounted for	Peaking at/ High loadings between	Significant effects in ANOVA	df	F	p
1	25.8%	112 m	switch x region switch x region x lat	3,57 6,114	3.58 32.78	< 0.05 < 0.05
2	6.9%	160 ms	letter type x region switch x region x lat	3,57 6,114	3.86 2.73	< 0.05 =0.053
3	16.9%	250 ms	letter type expression x lat switch x lat	1,19 2,38 2,38	10.92 4.54 4.54	< 0.01 < 0.05 < 0.05
4	5%	350 ms	letter type x region letter type x lat letter type x region x lat	3,57 2,38 6,114	3.99 4.39 3.16	< 0.05 < 0.05 < 0.05

Table 4.4 *PCA components of post-stimulus ERPs from the face task (switch by letter type)*

PCA Component	Variance accounted for	Peaking at/ High loadings between	Significant effects in ANOVA	df	F	p
1	26.3%	112 ms	letter type switch x region	1,19 3,57	10.42 8.00	< 0.01 < 0.01
2	6.2%	160 ms	switch x region switch x lat letter type x reg x lat switch x letter x lat switch only: letter type x lat	3,57 2,38 6,114 2,38 2,38	4.86 3.41 2.33 3.92 4.12	< 0.05 < 0.05 < 0.05 < 0.05 < 0.05
3	20%	250 ms	switch switch x lat letter type x region letter type x lat	1,19 2,38 3,57 2,38	14.09 10.53 5.49 7.76	< 0.01 < 0.001 < 0.05 < 0.01
4	10.1%	380 ms	letter type letter type x lat letter type x region x lat	1,19 2,38 6,114	23.18 18.42 8.09	< 0.001 < 0.001 < 0.001
5	31.3%	400 - 600 ms	letter type switch x region letter type x region x lat	1,19 3,57 6,114	14.29 6.14 7.86	< 0.01 < 0.01 < 0.01

Table 4.5 *PCA components of post-stimulus ERPs from the letter task (by switch by letter type)*

PCA Compo-nent	Variance accounted for	Peaking at/ High loadings between	Significant effects in ANOVA	df	F	p
1	26.7%	112 m	switch x region	3,57	8.19	< 0.01
2	6.2%	160 ms	expression switch x region switch x lat	1,19 3,57 2,38	5.03 4.95 3.53	< 0.05 < 0.05 < 0.05
3	21.1%	250 ms	switch switch x lat expression expression x region expression x region x lat	1,19 2,38 1,19 3.57 6,114	14.72 12.11 4.78 16.53 5.13	< 0.01 < 0.001 < 0.05 < 0.001 < 0.01
4	33.9%	350- 600 ms	switch x region expression x region x lat	3,57 6,114	7.2 2.50	< 0.01 < 0.05

Table 4.6 *PCA components of post-stimulus ERPs from the letter task (switch by emotional expression)*

PCA Compo-nent	Variance accounted for	Peaking at/ High loadings between	Significant effects in ANOVA	df	F	p
1	3.5%	120 ms	switch x region x lat	6,114	3.36	< 0.05
2	2.3%	155ms	switch x region x lat	6,114	2.47	< 0.05
3	13%	170-300 ms	switch switch x lat sw x region x lat	1,19 2,38 6,114	15.04 14.54 4.26	< 0.01 < 0.001 < 0.01
4	23%	300-550ms	switch x lat switch x region x lat	2,38 6,114	3.36 3.27	< 0.05 < 0.05
5	49%	435-1000ms	switch switch x region switch x lat switch x reg x lat task x switch x reg x lat	1,19 5,57 2,38 6,114 6,114	5.86 25.95 5.6 4.48 3.06	< 0.05 < 0.001 < 0.05 < 0.05 < 0.01

Table 4.7 *PCA components of the long CSI, (Exp. 4)*

5

A neural correlate of task-set interference

ABSTRACT

In task switching experiments performance is typically worse on switch trials, even when the task is cued well in advance – this 'residual switch cost' has been attributed to conflict from the competing task. Recent ERP studies have suggested a plausible neural correlate of task conflict, a switch-related negative polarity potential following stimulus onset. Alternatively, both the residual cost and the post-stimulus switch-induced negativity may be correlates of post-stimulus task-set reconfiguration. In Experiment 1, participants alternated between classifying letters (vowel/consonant) and digits (odd/even); alternation over long blocks removed the need for task-set reconfiguration. Presenting letters alongside digits slowed responses to the digits and elicited a post-stimulus negativity, consistent with conflict between the letter and digit tasks. The lack of response congruency effects for digit-letter stimuli suggested a locus of conflict at the level of task-set rather than response selection. Experiment 2 showed that the behavioural and ERP effects observed in Experiment 1 cannot be explained away by perceptual or familiarity factors. Experiment 3 examined the possibility that the task-set conflict observed in Experiment 1 is attentional (attention drawn inappropriately to letter features) by modifying the paradigm to enable 'bivalent unmapped' characters – e.g. letters that do not afford the irrelevant (letter) task. However, the finding that these characters did not slow responses suggests the locus of long-term, associative, task-set conflict is not attentional.

INTRODUCTION

To perform the appropriate action in an environment that affords multiple, often competing, actions goal-relevant information needs to be emphasised while irrelevant information needs to be suppressed. Among paradigms that have investigated such processes in the laboratory is the task-switching paradigm. It requires the participant to perform two (or more) tasks with a series of stimuli in a predictable or unpredictable sequence - in the latter case a cue identifies the task before each stimulus. A robust phenomenon observed in such

studies is the 'switch cost'- a performance decrement when the task changes compared to when it is repeated. Providing an opportunity to prepare by extending either the interval between the response and the next stimulus when task changes are predictable, or the cue-stimulus interval (CSI) when switching is unpredictable, usually results in a substantial reduction in switch cost, which has been interpreted by many as evidence for an advance act of task-set control: task-set reconfiguration (TSR, e.g., Rogers & Monsell, 1995; Meiran, 1996).

The 'residual' switch cost and task conflict

Although the switch cost tends to reduce with preparation, it is rarely eliminated. This seems to divide the processes causing the switch cost into two parts: one part that can be overcome by active preparation and another that cannot. One influential account of the latter, 'residual', switch cost proposes that task-set activation of the previously relevant task and task-set inhibition of the previously irrelevant task carry over into the subsequent trial, a phenomenon referred to as task-set inertia (Allport, Styles & Hsieh, 1994). These after-effects of the preceding trial result in conflict when the task changes. The fact that performance recovers to asymptote very soon after a switch- over one trial in predictable switching (Rogers & Monsell, 1995) and over 3-4 trials in unpredictable switching (Monsell, Sumner and Waters, 2003)- suggests that task-set inertia, or at least its component that contributes to the switch cost, is transient. However, task conflict might also be elicited by longer-lasting associations between stimuli and task-sets: if the stimulus was previously encountered in the context of the irrelevant (competing) task, performance is impaired, particularly on switch trials (Wylie & Allport, 2000; Waszak, Hommel, & Allport, 2003). Subsequently, this effect was shown to be due mainly to stimuli retrieving the competing tasks-set via the previously formed associations, though with small stimulus sets, there was also a contribution of negative learned associations: responses were slower for previously irrelevant stimuli (distractors) that became relevant in the current task (Waszak, Hommel, & Allport, 2005). Waszak and colleagues also showed associative effects to transfer to other (semantically related) stimuli (Waszak, Hommel, & Allport, 2004).

Levels of task conflict

Task-set inertia and/or stimulus-driven associative retrieval of task-set may cause conflict on at least two levels. First, they may result in some activation of the response appropriate to the previous task. When this response is different from that in the current task — as for *incongruent* stimuli — the result is 'response conflict', relative to the case of *congruent* stimuli, for which the response is the same in both tasks, so that activation of the irrelevant task's response will facilitate, or at least not compete with, the appropriate response. Second, task conflict may also arise in other components of the task-set, for example at the level of attentional selection of the relevant stimulus dimension, or in other hypothetical components of the task-set (e.g. task-goals). For example, there is lateral inhibition between task-set units in Brown, Reynolds and Braver's (2007) connectionist model of task-set control. We will refer henceforth to conflict between tasks at this superordinate level as 'set' or 'set-level' conflict. And we will use the term "task-conflict" as an umbrella term for both response-level and set-level conflict.

There is evidence of both response-level and set-level conflict in task-switching paradigms. Performance for incongruent stimuli is almost always worse than for congruent stimuli, indexing conflict at the level of response selection. That the congruence effect tends to be larger on switch compared to repeat trials indicates greater activation of the irrelevant S-R rules immediately following a switch in tasks, though congruence effects remain substantial well beyond the transient effects of a task-switch (e.g., Monsell et al., 2003). To examine set conflict, researchers have compared *bivalent* stimuli that afford both the relevant and irrelevant task with *univalent* stimuli that afford only the relevant task (Rogers & Monsell, 1995; Karayanidis, Coltheart, Michie & Murphy, 2003; Elchlepp, Lavric, Mizon & Monsell, 2011). In particular, one can contrast congruent bivalent stimuli, which afford both tasks but require the same response in the two (hence creating the possibility for set-level conflict, but facilitation at the response level) with univalent stimuli, which afford neither the other task, nor another response. Longer RTs and larger RT switch costs for congruent bivalent versus univalent stimuli suggest that conflict at the set level is often sufficient to outweigh the benefit of response-level facilitation (Rogers and Monsell, 1995; Aron, Monsell, Sahakian & Robbins, 2004; Steinhauser & Hübner, 2007).

Reconfiguration-based accounts of the residual switch cost

However, these two kinds of task conflict are not the only possible sources of the residual switch cost. There are at least two alternative accounts. One proposes that TSR consists of two stages, of which the first can be started and (if there is opportunity) completed before the stimulus, whereas the second stage can only start after stimulus onset thus leading to a switch cost even when there is ample opportunity for preparation (Rogers & Monsell, 1995; Rubinstein, Meyer & Evans, 2001; Meiran, Kessler, & Adi-Japha, 2008). The second stage has been argued (Rubinstein et al., 2001; Meiran, Kessler, & Adi-Japha, 2008) to involve de-coupling of task-set and S-R rules associated with the irrelevant stimulus dimension and/or "rule activation"- loading the S-R rules associated with the relevant dimension into working memory.

Another TSR-based interpretation of the residual switch cost is based on De Jong's (2000) 'failure to engage' account, in which anticipatory TSR is conceptualised as a binary all-or-none process that sometimes succeeds and sometimes fails. The 'residual' switch cost is the average of a mixture of RTs from trials with effective (complete) preparation — hence no switch cost—with RTs from trials with ineffective (i.e. no) preparation — and hence a switch cost as large as without preparation. De Jong (2000) and Niewenhuis and Monsell (2002) found that RT distributions from the alternating-runs paradigm were consistent with the mixture model. But it remains unclear why, if this account is correct, very long preparation intervals, allowing multiple preparation attempts, and strong incentives for preparation do not eventually achieve full preparation (Niewenhuis & Monsell, 2002).

An electrophysiological correlate of the residual switch cost: conflict or TSR?

The present investigation aims to distinguish between conflict- and TSR-based accounts of the residual cost by examining a brain potential that may reflect the processes that give rise to the residual switch cost- a protracted switch-induced negative polarity deflection over the central and posterior scalp starting from ~250 ms following stimulus onset and extending into (but not limited to) the range of the P3 component of the ERP (Karayanidis et al., 2003; Nicholson, Karayanidis, Poboka & Mitchie, 2005; Lavric, Monsell & Mizon, 2008; Elchlepp et al., 2011). This switch-repeat difference (which we label for brevity 'switch negativity') has been consistently found following substantial preparation intervals (e.g.,

Karayanidis et al., 2005; Lavric et al., 2008). The fact that in some cases it was possible to ascertain its presence in long CSI conditions that resulted in asymptotic switch cost (by using more than two CSIs, e.g., Nicholson et al., 2005) provides confidence that this ERP is indeed related to the residual switch cost.

We (Lavric et al., 2008) and others (e.g., Nicholson et al., 2005) have proposed that this component reflects enhanced conflict/ interference on switch trials, an interpretation in part motivated by reports of a similar conflict-related negativity with a parietal distribution (N450) in some ERP studies of Stroop interference (West, 2003). To test this proposal, a recent task-cuing study from our laboratory (Elchlepp et al., 2011) compared the magnitude of the switch negativity for bivalent versus univalent stimuli. In an earlier study, Karayanidis et al. (2003) examined the same contrast with predictable switching. Because univalent stimuli afford only one task in the context of the experiment, one might expect that the switch negativity usually observed following bivalent stimuli would be strongly attenuated or eliminated when stimuli are univalent. In both of the above mentioned studies, the negativity was reduced, but not eliminated. Noting that in their colour/shape identification experiment the univalent stimuli contained the perceptual dimension of the irrelevant task (e.g. shapes were presented in black, a colour not mapped to a response in the colour task, but a colour nonetheless), Elchlepp et al. (2011) proposed that univalent stimuli may have been associated with some activation of the irrelevant task-set, by virtue of affording attention to the dimension of the competing task, which resulted in set-level conflict, consistent with the presence of a reliable switch cost for the univalent stimuli in the long CSI condition.

However, an alternative explanation might also be possible. The fact that univalent stimuli cause minimal task-set conflict but still a non-trivial switch negativity was found could be seen as an indication that this brain potential is a reflection of post-stimulus TSR rather than task conflict. Because in two-stage TSR accounts both stages are obligatory for any stimulus on a task-switch trial, this provides a natural interpretation of a robust switch-repeat difference after the stimulus onset. Furthermore, the notion that post-stimulus TSR is qualitatively different from anticipatory (pre-stimulus) TSR (Rubinstein et al., 2001, Meiran, 1996) could explain why the post-stimulus switch negativity has distinct biophysical characteristics (different polarity) from the ERP correlate of pre-stimulus TSR-

a positive polarity switch-related potential typically seen in the last portion of the preparation interval leading up to the stimulus (e.g., Karayanidis et al., 2003; Nicholson et al., 2005; Lavric et al., 2008).

In the present experiments, we wished to exclude TSR as a source of post-stimulus ERP effects, and examine the consequences of task-conflict based on relatively long term associations between stimulus attributes and tasks and/or responses. Hence, tasks switched not within, but only between, relatively long blocks of trials. Evidence from predictable switching ('alternating runs') shows that recovery from a task-switch is complete on the second trial of a task run (Rogers & Monsell, 1995). Even with unpredictable switching recovery is asymptotic after 3 or 4 trials (Monsell, Sumner & Waters, 2003). Hence we would expect task-set reconfiguration to be completed within the first trial or two of a block. We could thus ask whether manipulations of task conflict (stimulus valence) in the absence of TSR or transient task-switches, using the same kind of stimuli as in ERP studies reporting a post-stimulus negativity on switch trials (e.g., Karayanidis et al., 2003; Nicholson et al., 2005), would elicit a brain potential of the same polarity and similar time-course and spatial distribution.

Experiment 5

If the post-stimulus switch negativity reflects task conflict, such conflict is likely to arise even in single task blocks for stimuli that previously afforded a different task (bivalent stimuli). Hence one would expect a similar negativity to emerge in the comparison of bivalent and univalent stimuli if a strong association had been formed between the irrelevant attribute in the bivalent stimuli and a competing task. To accomplish this we adapted a letter/digit task pair widely used in both behavioural and ERP task switching paradigms (e.g. Rogers & Monsell, 1995; Karayanidis et al., 2003; Nicholson et al., 2006). In an initial training session, participants classified a single letter presented on each trial as consonant or vowel. In a subsequent session, two kinds of blocks were interspersed. There were blocks of single-letter classification trials to reinforce the associations created by performing the letter task. There were also blocks in which the stimulus was a pair of characters including a digit, and the task was to classify it as odd/even. To create bivalent

stimuli a letter was combined with the digit (e.g. 1A, V5) so that the stimulus afforded a competing task (even though the letter task was never required in a digit-task block). To create a univalent stimulus a non-alphanumeric symbol was combined with the digit (as in #3) so that the stimulus afforded only one task. We expected task conflict on digit-letter trials, but not on digit-symbol trials and examined the ERPs for the presence of a negativity elicited by digit-letter relative to digit-symbol stimuli over the posterior scalp from about 250-300 ms following stimulus onset. To examine effects of response conflict, we contrasted bivalent incongruent stimuli (digit-letter stimuli whose component characters required different responses in the two classification tasks) with bivalent congruent stimuli (digit-letter stimuli whose component characters required the same response in the two tasks). To investigate effects of set conflict, we compared bivalent congruent stimuli to univalent (digit-symbol) stimuli.

In addition to investigating the effects of valence and congruency, we also manipulated the association between specific letters and performing the letter task (and the resulting response), to examine the role of stimulus-specific associations in generating task conflict (cf. Waszak et al., 2003). Of the letters used as the irrelevant character in the digit-task blocks some had been repeatedly classified in previous letter task blocks (*old* letters) and some occurred only as irrelevant characters in the digit-task blocks (*new* letters). To the extent that the associations causing task-conflict are stimulus-specific one would expect 'old' letters to elicit more conflict than 'new' letters. To the extent that associations are formed only between classes of stimuli (e.g. 'letters') and tasks, 'old' and 'new' letters should elicit similar degrees of conflict.

METHODS

Participants

Twenty four right handed students (8 female) aged 18 – 47 (M = 24, SD = 6.7) gave written informed consent to participate in the experiment, whose procedure was approved by the local Ethics Committee (School of Psychology, University of Exeter). Participants were paid £13 for completing two testing sessions.

Apparatus

The testing was run and behavioural data collected using E-prime 1.1 software (Psychology Software Tools, Sharpsburg, PA, USA) running on a standard PC with a 17'' CRT monitor; responses were recorded using a standard computer keyboard. The EEG was acquired using 64 active Ag/AgCl electrodes embedded in a cap connected to EEG amplifiers (ActiCap and BrainAmp, Brain Products, Munich, Germany). There were 61 electrodes on the scalp in an extended 10-20 configuration, one below the right eye, and one on each earlobe. Electrode locations were adjusted using a CMS ultrasound digitizer (Zebris Medical, Isny, Germany) and their impedances kept below 10kΩ.

Stimuli, tasks and procedure

To exploit the beneficial effect of sleep on consolidation of content learned in simple tasks with motor responses (Nishida & Walker, 2007), the testing was run over two consecutive days: a 20 minute training session on day 1 and a 1.25 hours session on the following day; EEG data were collected only in the second session.

On Day 1 over four blocks (see Figure 5.1), each of 144 trials, Participants classified a single letter as vowel or consonant by pressing the left or right arrow key, with the assignment of keys to the vowel/consonant categories counterbalanced over participants. Each trial started with a blank (white) screen for 500 ms, followed by a black fixation cross in the centre for 500 ms, followed by presentation in the same location of one of four letters in lower case Lucida Console font (subtending 0.5°-1° of visual angle). The stimulus remained on the screen until a response was made. Feedback was given only following an error: "ERROR" displayed for 1500 ms.

On Day 2 three 72-trial blocks (blocks 2, 4 and 6) of the vowel/consonant classification task practiced on Day 1 were interspersed among four blocks (1, 3, 5, 7) in which the task was to classify a digit from the set 1-6 as odd (left key) or even (right key). In Block 1 (48 trials), the digit classification task was introduced by presenting a single digit. Blocks 5 and 7 (144 trials each) were critical for investigating task-set conflict. Here, the to be classified digit was paired with either a letter (bivalent stimulus) or with one of six non-alphanumeric characters (or 'symbols': # * ; ¤ { }). No classification responses to symbols were required in the experiment, so digit-symbol stimuli were 'univalent'.
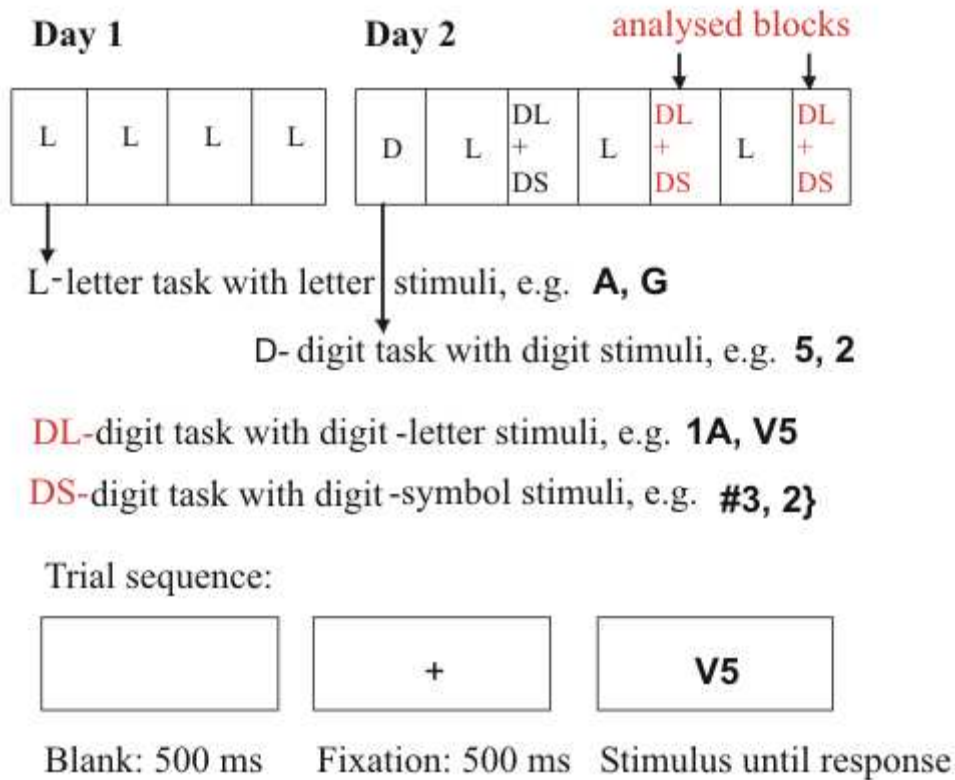
Figure 5.1 *Details of the paradigm and example of stimuli*

Amongst the bivalent (digit-letter) stimuli, 2/3 contained 'old' letters presented on Day 1
and extensively re-exposed in the letter classification blocks on day 2 (17 times each per
block) and 1/3 contained 'new' letters not seen on Day 1 and only presented twice in the
letter classification block preceding a critical digit classification block. Specifically, one
'new' vowel and one 'new' consonant was introduced (presented alone twice each) in each
of blocks 4 and 6 to avoid 'novelty' effects in the ERPs when they were subsequently
presented alongside digits in the following digit classification block. Two four-letter sets
(*a, i, r, v* and *e, u, c, n*) were assigned the 'old' and 'new' status, respectively, for half of the
participants, while for the other half of the participants this assignment was reversed. Block
3 (144 trials) was a practice block for the odd/even classification with compound stimuli.
As in Blocks 5 and 7, 2/3 of its bivalent stimuli contained 'old' and 1/3 'new' letters (in this
block the new letters were consonants *d* and *f* for all participants). In all digit classification
blocks with compound stimuli (i.e. blocks 3, 5 and 7), half of the stimuli were bivalent and
half univalent. Every letter and every symbol was paired equally often with each digit and
the two orders of the characters in the compound (e.g. *2d* and *d2*) were equally represented

for every pair of characters. The structure of a trial was the same on Day 2 as on Day 1 (see Figure 5.1).

EEG/ERPs

The EEG was sampled continuously from 64 channels at 500 Hz with a bandpass of 0.016-100 Hz, with the reference at Cz and the ground at AFz. Following offline filtering with a 20 Hz low-pass filter (24 dB/oct) and re-referencing to the linked ears, the EEG was segmented into stimulus-locked epochs, consisting of a -100 to 0 ms pre-stimulus baseline and a 500 ms post-stimulus segment. After baseline correction, segments associated with performance errors, as well as those containing ocular, muscle and other artifacts were discarded by means of visual inspection. The remaining EEG segments were averaged for every participant and experimental condition.

To limit the number of statistical tests and improve the signal-to-noise ratio, differences between experimental conditions were assessed by comparing the amplitude of the ERPs averaged within temporal ranges (time-windows). The identification of time-windows was based on the scalp distribution (topography) of the difference between conditions. A time-window was defined as the interval of relative topographic stability between abrupt topographic changes- the changes in topography were identified with Topographic Analysis of Variance (TANOVA, Pasqual-Marqui, Michel & Lehmann 1994), a method that treats the difference between two scalp maps as a vector over the scalp electrodes. The magnitude of the difference between the maps (the topographic dissimilarity) can be expressed as the vector length- the sum of squares of all its components (difference at each electrode), resulting in a value that expresses the topographic dissimilarity. For every experimental contrast (e.g. univalent versus bivalent conditions), we computed the difference wave and used TANOVA to assess the topographic dissimilarity of adjacent time-points in the difference wave. To ensure sensitivity to changes in topography that are more graded, we ran TANOVAs with a lag of 2, 10 and 20 ms (i.e. computed the dissimilarity between each time-point and the time-point 2, 10 or 20 ms back). The resulting dissimilarity time-courses were then used to identify the intervals of relative topographic stability, which were subsequently used as time-windows in the statistical analysis.

ERP amplitudes in these time-windows were averaged and submitted to repeated measures ANOVAs. To assess potential interactions with scalp regions in the ANOVAs, ERPs were averaged for 7 groups of electrodes in each hemisphere, ignoring the midline electrodes, to yield average scores for 7 regions on the left: anterior frontal (FP1, AF1, AF7, F5), lateral frontal (F7, F9, FT7), medial frontal (F1, F3, FC1, FC3), posterior frontal (FC5, C1, C3, C5), temporal (T7, TP7, CP5), parietal (CP1, CP3, P1, P3, PO1), occipital (P5, P7, PO7, O1) and the corresponding regions on the right. Region and hemisphere were factors in the ANOVA along with the factors bi-/univalent, old/new and congruent/incongruent. Significance levels were adjusted using the Huynh-Feldt correction for violations of sphericity (but unadjusted degrees of freedom are reported). When significant interactions of switch/repeat with region were found, two-tailed t-tests were performed to identify regions with significant differences using the Bonferroni correction to control for the inflation of type 1 error in multiple tests.

RESULTS

Behavioural results

Planned contrasts by means of t-tests showed that response times were longer for bivalent (digit-letter) stimuli (603 ms) than for univalent (digit-symbol) stimuli (579 ms), a mean difference of 25±5ms, $t(23) = 5.37$; $p < 0.001$, suggesting greater interference in the digit classification task from the letter than from the symbol. This was true even when comparing bivalent congruent stimuli (601 ms) to univalent stimuli, a difference of 23±5ms, $t(23) = 4.80$; $p < 0.001$. An ANOVA on the bivalent stimuli with factors letter type ('old' versus 'new') and congruency found digit classification RTs to be insensitive to whether digits were paired with letters that had a well practiced response mappings in the irrelevant (letter) task ('old' letters, 604 ms), or with letters seen only twice in the immediately preceding letter-task block ('new' letters, 603 ms), $p > 0.1$. Response congruency, that is whether the digit and letter in the compound stimulus were mapped to the same ('congruent'), or different ('incongruent') response keys had only a minor (non-significant) effect on RTs (congruent = 601 ms; incongruent = 606 ms), $p > 0.1$, which did not interact with the old/new letter manipulations, $p > 0.1$.

There were no significant differences in error rates between bivalent (5.1%) and univalent (5.3%) stimuli, or bivalent congruent (5.4%) and univalent (5.3%) stimuli. The

ANOVA on bivalent stimuli with factors letter type ('old' versus 'new') and congruency did not reveal any significant differences between old (4.8%) and new (5.2%) or congruent (5.4%) and incongruent (4.7%) stimuli, nor was the interaction between these manipulations reliable.

ERP results

Bivalent versus univalent

For the bivalent versus univalent contrast the following time-windows were defined: 130-150 ms, 170-200 ms, 210-270 ms, 350-430 ms and 460-480 ms. Between 130 and 150 ms, amplitudes in the occipital region of the left hemisphere were more negative for bivalent than for univalent trials; however, this effect did not reach significance when corrected (valence by hemisphere, $F(1, 23) = 4.13$, $p = 0.054$; valence by region in the left hemisphere $F(6,138) = 3.67$, $p < 0.05$; t-test in the left occipital region, $t(23) = -2.18$, $p = 0.28$, corrected; 0.04, uncorrected). The 170-200 ms time-window seems to capture the peak of the N1 (see Figure 5.2) which had greater (more negative) amplitude in response to univalent stimuli: main effect of valence, $F(1, 23) = 6.1$, $p < 0.05$; region by valence interaction, $F(6,138) = 3.87$, $p < 0.05$. In the time window from 210 to 270 ms, valence interacted reliably with region, $F(6,138) = 53.23$, $p < 0.001$. In the left, $t(23) = -7.85$, $p < 0.001$ and right, $t(23) = -5.75$, $p < 0.001$ occipital regions, amplitudes were more negative in the bivalent condition than in the univalent condition, possibly reflecting a posterior Selection Negativity (SN), whose amplitude was larger following bivalent stimuli, or a delayed/more variable N1 in the bivalent condition (see Figure 5.2).
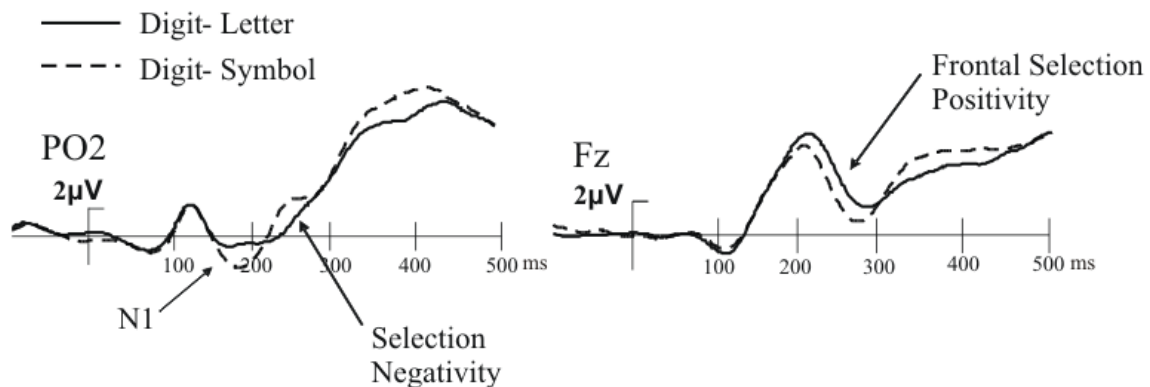

Figure 5.2 *ERPs for Digit- Letter and Digit- Symbol trials in PO2 and Fz*

While for univalent trials the preceding N1 showed a sharp peak, which largely recovered to baseline by 210-270 ms, for bivalent trials the N1 seemed broader, possibly due to greater variability in its latency. Concurrent with this posterior negativity, fronto-central amplitudes were more positive for the bivalent condition than the univalent condition: anterior frontal left, $t(23) = 5.37$, $p < 0.001$ and right, $t(23) = 4.59$, $p < 0.01$; lateral frontal left, $t(23) = 5.38$, $p < 0.001$ and right, $t(23) = 3.78$, $p < 0.05$; medial frontal left, $t(23) = 5.36$, $p < 0.001$ and right, $t(23) = 5.31$, $p < 0.001$; posterior frontal left, $t(23) = 4.02$, $p < 0.01$. The 350-430 ms time-window was associated with a reliable negativity for the bivalent condition relative to the univalent condition: main effect of valence, $F(1, 23) = 16.08$, $p < 0.01$, an effect that was maximal in the posterior scalp regions (see Figures 5.2 and 5.3A).
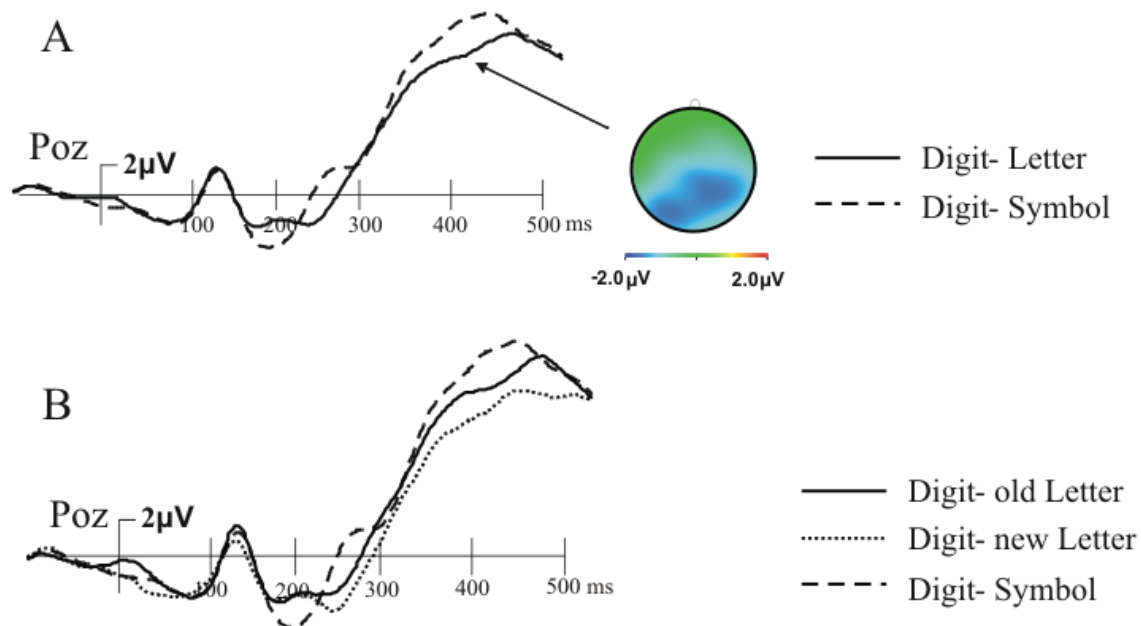
Figure 5.3 *ERPs for Digit- Letter and Digit- Symbol and topography of the difference(A), ERPs for digits paired with old letter, new letter and symbol (B)*
'Old' versus 'new' letters

For the 'old' versus 'new' contrast the following time-windows were defined: 110-130 ms, 160-180 ms, 220-280 ms, 330-390 ms and 420-480 ms. Only the last time-window between 420-480 ms showed reliable differences (main effect of old/new, $F(1, 23) = 5.63$,

$p < 0.05$) with amplitudes for 'old' letters being more positive compared to new in parietal and occipital regions (possibly a larger P3b for 'old', see Figure 5.3B).

Response conflict: congruent versus incongruent

Although there were no reliable effects of congruency in the behavioural data, we examined the possibility that the ERP effects of valence might reflect response-level conflict, by analyzing the effects of congruency in the three time-windows associated with robust effects of valence (170-200 ms, 210-270 ms, 350-430 ms). There were insufficient trials to examine the congruence by old/new interaction in the ERPs. Because there were twice as many 'old' than 'new' letter trials and since one would expect congruency effects to be more pronounced for the more practiced stimuli, congruency analyses were run confined to bivalent stimuli containing 'old' letters. No reliable effects of congruency were found in these analyses in any of the three time-windows under scrutiny (170-200 ms, 210-270 ms, 350-430 ms).

Set conflict: congruent versus univalent

To determine whether the valence effects may instead reflect set-level conflict, which yielded a robust effect in the RT data, we contrasted the bivalent congruent condition with the univalent condition for the same three time-windows associated with effects of valence (170-200 ms, 210-270 ms, 350-430 ms). Robust effects were also found in the ERPs- in all three time-windows, mirroring the differences between all bivalent trials and the univalent trials (see Figure 5.4). Relative to univalent ERPs, congruent ERPs showed a reduced
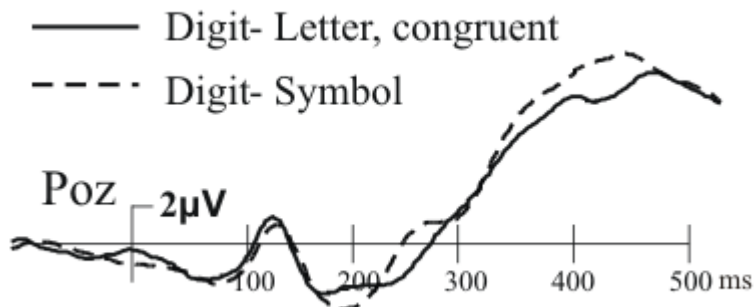

Figure 5.4 *ERPs for congruent digit-letter trials and digit-symbol trials*

amplitude of N1 (170-200 ms), $F(1, 23) = 5.86$, $p < 0.05$, greater posterior Selection Negativity, accompanied by anterior positivity (condition by region interaction at 210-270 ms, $F(6, 138) = 32.63$, $p < 0.001$) and more negative ERPs over posterior regions at longer latencies (350-430ms), as indicated by the condition by region, $F(6, 138) = 10.01$, $p < 0.001$, and condition by region by hemisphere, $F(6, 138) = 4.44$, $p < 0.01$, interactions, and the follow-up t-tests in the posterior regions (left occipital, $t(23) = 2.71$; $p < 0.05$; left and right parietal, $t(23) = 2.58$; $p = 0.068$, $t(23) = 2.55$; $p = 0.072$).

DISCUSSION

We found clear effects of valence on performance on the digit task: RTs were longer for bivalent (digit-letter) stimuli than for univalent (digit-symbol) stimuli. Moreover, RTs for congruent stimuli were reliably longer than for univalent stimuli, and there was little difference between congruent and incongruent stimuli. This pattern indicates set-level rather than response-level conflict. In the ERPs, bivalent stimuli elicited the predicted negativity over the parietal scalp in the ~300-500 ms range when compared to univalent stimuli, and there was no discernable effect of response congruence, supporting the notion of this negativity as a marker of task conflict. In its polarity, timing and scalp-distribution it closely resembled the post-stimulus switch-repeat negativity previously documented in task-switching paradigms (see Introduction and Figure 2.6, components 4 and 5 for examples of topography). There was no evidence of a contribution from stimulus-specific associations or bindings between stimulus and task or response, as 'old' and 'new' letters appeared to slow responses to bivalent stimuli to an equivalent extent. Hence the task-conflict seen here appears to result from the training having created an association from the letter class to attentional settings or to the goal of classifying the letter, rather than from specific stimuli.

There are, however, alternative interpretations of the above findings. First, letters are arguably more familiar both individually and as a class than the alphanumeric symbols. Hence, what we have interpreted as task-conflict due to training on the letters could instead reflect the greater attention-grabbing power of familiar letters. Secondly, the task may have an element of visual search: the participant may have to "find" the digit in the pair. Perhaps the digit is easier to find next to a symbol than next to a letter, because it is easier to discriminate from a symbol. Indeed, in addition to the valence-related negativity in the 300-

500 ms range, there were also earlier differences between the bivalent and univalent ERPs-a delayed or more variable N1 peak on bivalent trials, probably accompanied by greater posterior Selection Negativity for the bivalent stimuli. These ERP components have been implicated in spatial selection (N1) and feature selection (Selection Negativity) and hence might reflect differences in ease of attentional selection of the relevant category or character. To examine the possible contribution of such intrinsic differences between the letter and symbol characters, we ran a second experiment.

Experiment 6

Experiment 6 was designed as a control for the valence manipulation in Experiment 5. The critical blocks (those containing the digit classification task and compound stimuli) were constructed in just the same way in the two experiments. The essential difference was that in Experiment 6 there was no exposure to the letter classification task at any point. Thus, one could examine behavioural and electrophysiological differences between digit-letter (bivalent in Experiment 5) and digit-symbol (univalent in Experiment 5) stimuli that were not due to the prior involvement of a component of the stimulus in another task during the experiment. The procedural equivalence of the critical phase of the two experiments makes direct comparisons between the two straightforward.

METHOD

Participants, apparatus, stimuli and procedure

Sixteen right handed University of Exeter students, 12 female, 4 male, aged 18-45 (M = 23, SD = 6.6), were paid £10 for their participation following informed written consent (see Experiment 5). The apparatus and EEG set-up and analysis procedures were as in Experiment 5. There was now a single session (see Figure 5.5), just like the second session in Experiment 5, with one exception: in blocks 2, 4 and 6 the letter (vowel/consonant classification) task was replaced with a 'filler' classification task whose role was to maintain the same overall demands and duration of the testing session as Experiment 5. Stimuli for the filler task were black and white pictures of an animal (horse, mouse, duck) or an object (comb, ladder, key), which participants classified as living/non-living using the same keys as those used in the digit task.
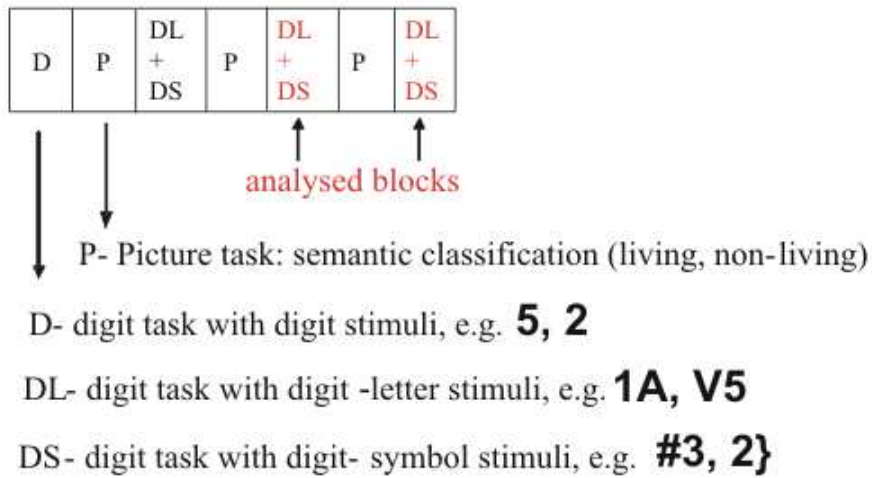
Figure 5.5 *Order of blocks and examples of stimuli for Experiment 6*

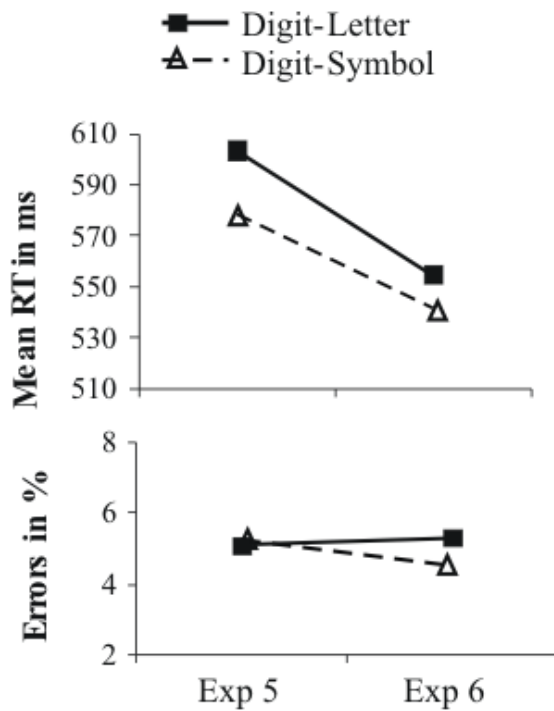## RESULTS

Behavioural results

Figure 5.6 *Behavioural results of Experiments 5 and 6*

Planned contrasts by means of t-tests found that responses to bivalent[9] (digit-letter) stimuli (554 ms) were slower than those to univalent (digit-symbol) stimuli (542 ms), $t(15)$ = -2.32; p< 0.05 (see Figure 5.6). However, a t-test comparing the bivalent-univalent RT difference in the two experiments found this difference to be significantly reduced in Experiment 6, $t(15)$ = -1.74; p< 0.05, one-tailed, to about half of that in Experiment 5 (13 versus 25 ms). As in Experiment 5, no reliable difference was found in error rate between bivalent (5.3%) and univalent (4.5%) stimuli, nor was this difference (0.8 ± 0.6%) reliably different from that in Experiment 5 (-0.2 ± 0.6%).

ERP results

Four time bins were extracted with the method described above (150 – 190 ms, 230 – 270 ms, 300 – 360 ms, 460 – 500 ms) and amplitudes averaged within these were submitted to repeated measures ANOVAs with the factors "bivalent" (digit + letter) / "univalent" (digit + symbol), region and hemisphere. In the time window between 150 – 190 ms valence interacted reliably with region, $F(6, 90) = 11.79$, $p < 0.001$ (see Figure 5.7). Follow up region-wise t-tests showed more negative amplitudes, i.e., a larger N1 for digit-symbol than digit-letter stimuli in the occipital region of the left hemisphere, $t(15) = 4.05$; p< 0.05. Between 230 – 270 ms valence interacted with region, $F(6, 90) = 6.73$, $p < 0.05$, this time amplitudes were more negative for digit-letter, again in the left occipital region of the scalp, $t(15) = -4.18$; p< 0.05. Between 300 – 360 ms a main effect of valence was found $F(1, 23) = 9.02$, $p < 0.01$ with amplitudes being more negative for digit- letter than digit-symbol trials in fronto-central areas of the scalp. In the 460 – 500 ms time-window there was a reliable interaction between region and valence, $F(6,90) = 4.36$; $p < 0.05$, but no scalp regions showed reliable effects of valence after correction.

Comparison of ERPs in Experiments 5 and 6

Digit-letter and digit-symbol ERPs of both experiments are shown in Figures 5.7 and 5.8. For the cross-study comparison only time-windows that showed reliable bivalent versus univalent differences in either of the experiments were considered. The resulting time bins

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[9] Because letters were not associated in Experiment 6 with any explicit task or set of responses, the terms 'bivalent' and 'univalent' are not entirely appropriate for referring to digit-letter and digit-symbol stimuli. We do, however, use them for the ease of exposition. For the same reason, the congruency factor (whose levels- congruent versus incongruent were equally represented in Experiment 5) is undefined here.

were 150 – 200 ms (including 150 – 190 ms from Experiment 6 and 170 – 200 ms from Experiment 5), 210 – 270 ms (including 210 – 270 ms from Experiment 5 and 230 – 270 ms from Experiment 6), 300 – 360 ms (reliable differences in Experiment 6) and 350 – 430 ms (reliable differences in Experiment 5). The amplitudes of the ERPs from both experiments were averaged in these time bins and submitted to an ANOVA with valence, region and hemisphere as repeated measures factors and experiment as between-subjects
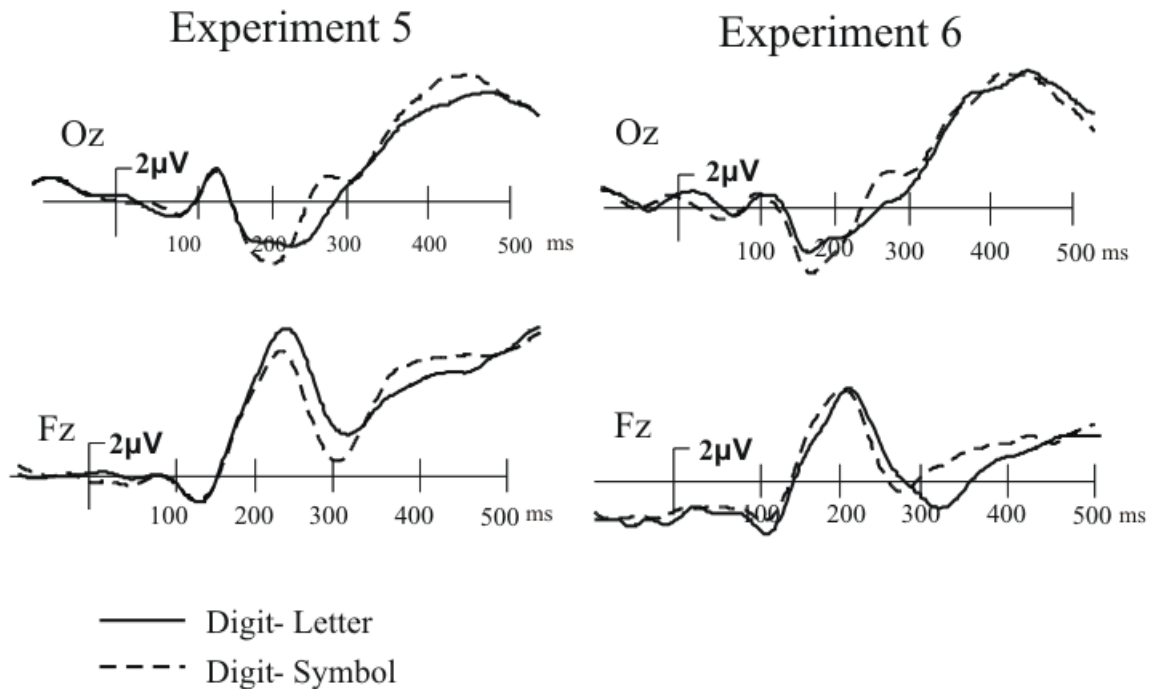
Figure 5.7 *ERPs for Digit- Letter and Digit- Symbol trials in Experiment 5 and 6*
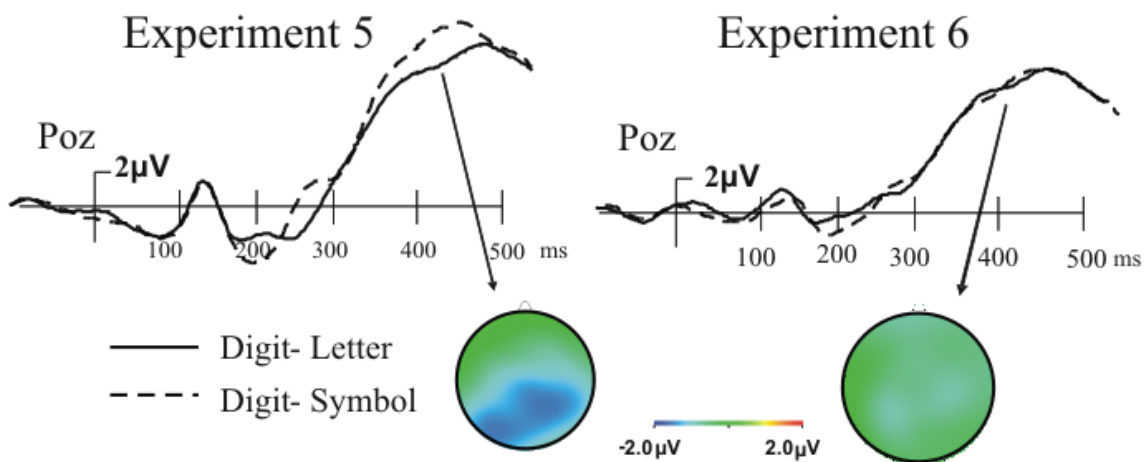
Figure 5.8 *Digit- Letter and Digit- Symbol ERPs and the topographies of their difference*

factor. Corrections for departures from sphericity and multiple comparisons, if necessary, were applied as described above.

The critical interactions were those involving valence and experiment. Such interactions were found in three of the four time-windows under scrutiny: 150 – 200 ms, 300 – 360 ms and 350 – 430 ms. In the earliest time-window (150 – 200 ms), the valence x experiment x region, $F(6,228) = 2.85$, p=0.05 and valence x experiment x region x hemisphere, $F(6,228) = 3.52$, $p = 0.021$ interactions were driven by differences in the laterality of the N1 effect in the two experiments, rather than in N1 amplitude, as indicated by the presence of reliable/marginally reliable effects in both experiments (Experiment 5: right occipital region, $t(23) = -3.44$, $p < 0.05$; Experiment 6: left occipital region, $t(15) = -3.45$, $p = 0.056$). At 300 – 360 ms, the significant valence x experiment x region interaction, $F(6,228) = 3.37$, $p < 0.033$ reflected bivalence-elicited negativities with a different distribution in Experiment 6 (anterior maximum, shown by significant valence effects in the right anterior frontal, $t(15) = -3.64$, $p < 0.05$, lateral frontal, $t(15) = -3.61$, $p < 0.05$, medial frontal, $t(15) = -4.21$, $p < 0.05$ and posterior frontal, $t(15) = -3.51$, $p < 0.05$, as well as left medial frontal scalp regions, $t(15) = -3.58$, $p < 0.05$) compared to Experiment 5 (posterior maximum, indicated by marginally reliable valence effects in the right parietal and temporal regions, $t(23) = -3.13$, p = 0.07 and $t(23) = -3.22$, $p = 0.056$, respectively).

Finally, in the 350 – 430 ms time-window the reliable valence x experiment x region interaction (see Figure 5.8), $F(6,228) = 4.48$, $p < 0.018$ reflected the presence of a robust and widespread bivalence-induced negativity in Experiment 5 with a central-posterior maximum reliable bilaterally in the frontal posterior, ($t_{left}(23) = -3.54$, $p < 0.05$; $t_{right}(23) = -3.81$, $p < 0.05$), parietal, ($t_{left}(23) = -4.97$, $p < 0.05$; $t_{right}(23) = -5.94$, $p < 0.05$), temporal ($ll_{eft}(23) = -3.13$, $p = 0.07$; $t_{right}(23) = -4.74$, $p < 0.05$) and occipital ($t_{left}(23) = -4.82$, $p < 0.05$; $t_{right}(23) = -4.94$, $p < 0.05$) scalp regions and its absence in Experiment 6, for which no scalp region showed reliable effects of valence (see Figure 5.8).

DISCUSSION

Experiment 6 showed that even in the absence of any letter task (or requirement to respond to letters) throughout the experiment, pairing the digit with a letter slowed the odd versus even classification of a digit relative to pairing the digit with a non-alphanumeric character (symbol). However, this difference was reliably smaller in Experiment 6 compared to

Experiment 5. We therefore conclude that about half of the effect of the character presented alongside the digit in Experiment 5 depended on its association with a competing task and hence indexed task-level conflict.

The two earliest electrophysiological effects of the character paired with the digit that were observed in Experiment 5 (the reduction/delay in the N1 component and larger Selection Negativity for digit-letter trials), were also found in Experiment 6 (see Figure 5.7). Hence, these perceptual/attentional effects are unlikely to reflect task conflict, but likely to reflect 'attention' pulling by letters relative to symbols and/or perceptual differences between digit-letter and digit-symbol stimuli. But crucially, the longer-latency ERP effect of valence (300-500 ms post-stimulus onset), which most closely resembled previously reported switch negativities in the same latency range in task-cuing, was confined to Experiment 5- indeed there was no sign of this effect in Experiment 6 (see Figure 5.8), thus strengthening its interpretation as a marker of task conflict.

We now return to the robust RT and ERP differences between the congruent bivalent stimuli and univalent stimuli in Experiment 5 which, along with the absence of effects of response congruency, convincingly point to the set level as the primary (or only) locus of task conflict in Experiment 5. What processes might set-level conflict reflect? At least two possibilities suggest themselves. First, there may be some carry-over of the attentional settings of the irrelevant task-set, e.g. tuning to letter features persisting from the preceding letter classification block, and/or reactivated by the presence of letter features. This could lead to letters in digit-letter stimuli capturing attention more than symbols in the digit-symbol stimuli, thus delaying selection and subsequent processing of the digit. Second, even partial processing of the letter component of a compound stimulus could lead in Experiment 5 to the (re)activation of the task goal "classify the letter" and this might compete with the goal of classifying the digit. However, Experiments 6 cannot clarify whether the conflict measured in Experiment 5 arises at the attentional level. Letters paired with digits in Experiment 6 did interfere more with performance than symbols paired with digits suggesting early attentional effects could be responsible. It is, however, also possible that the stimulus compound digit-letter is more difficult to process (i.e. it is harder to isolate the digit when it has a letter next to it) than the stimulus compound digit-symbol due to a greater familiarity of the digit-letter combination than the digit-symbol combination. In this

case the interference would not be at the attentional level. Experiment 6 was not designed to rule out or confirm possible effects of attention on task-set interference. To assess the contribution of attentional conflict to task-set interference Experiment 7 was designed. It uses a modified behavioural version of the paradigm from Experiment 5. The key change is the introduction on Day 2 of stimuli that are of the same type as the ones practiced on Day 1, but do not afford the Day 1 task (e.g. 'new' letters that do not afford the Day 1 letter task). If the set conflict observed in Experiment 5 arose (largely) from inappropriate attention to letters, irrespective of task/response affordance, 'new' letters should interfere significantly with the processing of the relevant character.

Experiment 7

The aim of the present experiment is to examine the possibility that the task conflict effects observed in Experiment 5 arose (largely) at the stage of attentional selection. Note that under this account conflict occurs even before the irrelevant character is subjected to classification and well before the corresponding stimulus-response rule may become activated; the mere presence of a character of the same type (class) as those from the irrelevant task can elicit conflict between task-sets.

Within the general paradigm of Experiment 5, let us consider the theoretical possibility of introducing another kind of irrelevant character- letters that do not afford the vowel-consonant categorisation (by implication, they would also not afford responses in the letter task). Despite not being classifiable according to the criteria of the irrelevant task, such letters may still trigger conflict at the level of attentional selection because of their overlap in perceptual features with the classifiable letters. Evidently, there could not be such stimuli in Experiment 5, because all English letters can be categorised as vowels or consonants. In the present experiment, we replaced the non-arbitrary phonological-semantic categories of vowels and consonants with arbitrary categories containing one member each. In other words, the Day 1 classification task was replaced by an identification task in which individual characters were arbitrarily mapped onto button presses. (These characters were letters for half of the participants and digits for the remaining participants, see Methods; the following will describe the situation for the group that practiced on letters). Following

practice with these mappings, participants were taught mappings of non-alphanumeric symbols onto the same set of button presses. Subsequently, symbols were paired with:

(1) the 'old', pre-trained, letters (resulting in bivalent compound stimuli), or

(2) characters that were of the same perceptual type but that were not previously encountered during the experiment- 'new' letters (resulting in 'bivalent unmapped' stimuli), or

(3) characters of a type not encountered in the experiment (digits), resulting in univalent stimuli.

Under an attentional conflict account, bivalent unmapped stimuli should elicit task-set conflict and hence poorer performance relative to univalent stimuli. In the absence of additional sources of conflict, bivalent unmapped stimuli should elicit the same amount of conflict as bivalent (mapped) stimuli.

METHODS

Participants

Sixteen right handed students at the University of Exeter, 10 female, 6 male, aged 20-21 (mean = 20.75), volunteered to participate in the experiment and provided informed written consent prior to testing (see Experiment 5).

Apparatus

The apparatus was the same as that used to collect the behavioural data in Experiments 5 and 6 with the exception that responses were recorded via an E-prime button box with four buttons (Psychology Software Tools, Sharpsburg, PA, USA), rather than a standard keyboard. This change was made to avoid potential inference from prior typing skill with the one-letter-per-key identification task used in the current experiment.

Stimuli and procedure

The experimental design (see Figure 5.9) was closely modelled on that of Experiment 5: over two sessions run on consecutive days, participants were first introduced to one task on day 1, followed on day 2 by another task interspersed with blocks of the task from day 1. As in Experiment 5, there were two critical test blocks on day 2 consisting of compound stimuli, many of which contained stimuli previously seen separately in the two tasks.

Day 1				Day 2							
trials 80	80	80	80	80	80	80	16*	40	120	40	120
L/D	L/D	L/D	L/D	S	S	L/D	SL + SD	L/D	SL + SD	L/D	SL + SD

L- Letter identification task (button box) with letter stimuli;**J, C, K, N, D, V, F, R** (only 4 presented on day 1)

D- Digit identification task (button box) with digit stimuli;   1 to 9 except 5 (only 4 presented on day 1)

S- Symbol identification task (button box) with symbol stimul   i; #, *, }, "

SL- symbol task with symbol-letter stimuli (if letter task was done on day 1, letters can be old or new otherwise they are all new)

SD- symbol task with digit-symbol stimuli, (if digit task was done on day 1, digits can be old or new otherwise they are all new)

*Introduced all symbol stimuli with digits 0 and 5 and equal numbers of old and new letters

Figure 5.9 *Paradigm and example stimuli of Experiment 7*

There were also important changes to the tasks and stimuli used in Experiment 5. The two classification tasks from Experiment 5 (vowel versus consonant and odd versus even) were replaced with two tasks each of which relied on arbitrary one-to-one mapping between four characters and four buttons. On day 1, half the participants did a letter task and half of the participants did a digit task for a total of four blocks (144 trials each). On day 2, all participants first learned the 'symbol' task- a set of one-to-one mappings between the symbols # } " * and four buttons. Two blocks of the symbol task (80 trials each) were followed by one block (80 trials) of re-exposure to the task performed on day 1 with letters or digits (depending on the counterbalancing condition to which the participant was assigned). This was followed by a short practice block (16 trials) of the symbol task with compound symbol-letter and symbol-digit stimuli. The letters and digits that appeared alongside symbols in this block were not part of the sets used subsequently in the critical test blocks. This short practice with compounds was followed by one block (40 trials) of re-exposure to the day 1 task with single-character stimuli (letters or digits), then the first test block (120 trials) with compound symbol-letter and symbol-digit stimuli, then another re-exposure block (40 trials) followed by the second test block (120 trials) with compound stimuli.

As in Experiment 5, the critical stimuli were the compound stimuli in the two test blocks. These were of three types: (non-alphanumeric) symbols presented alongside 'old' characters from Day 1 constituted the bivalent stimuli; symbols presented alongside

characters of the same type (e.g. letters) as those on day 1 task, but not seen previously in the experiment (and thus not mapped onto a response) constituted the 'bivalent unmapped' stimuli; finally, symbols presented alongside a character of the type (e.g. digits) not seen in the task practiced on Day 1 constituted the univalent stimuli. To ensure that the differences between the conditions were not due to perceptual, familiarity or other differences between characters (letters versus digits, some letters versus others, some digits versus others), four sets of four characters were created: jckn; dvfr; 9714; 2683, each mapped onto the four buttons of the button box in this order from left to right. Among the participants who did the letter task on day 1 (half of the whole sample), half responded to letters j, c, k, and n on Days 1 and 2 and saw both them and the letters d, v, f and r (which were not mapped to responses in the letter task) in compound stimuli alongside symbols on Day 2. For the other half of participants who did the letter task on Day 1, the letter sets were exchanged. Both groups saw all eight digits on Day 2. The same counterbalancing scheme was applied to the digit sets for the participants who did the digit task on Day 1. Thus, each character occurred as an irrelevant character with equal frequency, but 4 of them had been repeatedly identified in the single-character blocks.

As in Experiment 5, two new letters (or digits) were presented in each of the two test blocks; the two presented in the first test block were removed to preserve a constant ratio of four 'old' to two 'new' alphanumeric characters of the type seen on day 1. All the characters presented in any given block of trials during the experiment were equiprobable in that block, e.g. for a participant that did the letter task on day 1, in a critical test block on day 2 each of the 18 characters presented (4 'old' letters, 2 'new' letters, 8 digits, 4 symbols) occurred with equal frequency. In compound stimuli, each character was presented on the left and right with equal probability. As each response mapped to one of four buttons, on bivalent trials, 25% of bivalent stimuli were congruent and 75% incongruent.

The time course of one trial was as follows. Each trial consisted of a black fixation dot presented for 1500 ms against a white background followed by the stimulus presented centrally in black Arial font (0.5°-1° visual angle) until the response was made. If the response was incorrect, or there was no response within 3 seconds, the word 'Error' was displayed for 1500 ms.

RESULTS

Planned pairwise comparisons found that the slowing in responses for bivalent stimuli (655 ms) relative to univalent stimuli (642 ms) stimuli was not statistically significant, $t(15)=$ 1.59, $p = 0.13$. RTs for bivalent unmapped stimuli (639 ms) were not longer than those for univalent stimuli, $t(15)= -0.28$, p = 0.78. Bivalent and bivalent unmapped conditions did not diverge reliably in their RTs, $t(15)= 1.43$, $p = 0.17$. There was a reliable congruency effect for RTs: congruent, 619 ms; incongruent, 664 ms; $t(15)= 2.28$, $p < 0.05$. RTs for incongruent stimuli were longer than those for univalent stimuli, $t(15)= 2.14$, $p = 0.05$. The trend for the RTs for congruent stimuli to be shorter than those for the univalent stimuli failed to reach significance, $t(15)= -1.53$, $p = 0.17$.

The same set of contrasts run to compare the error rates for the univalent (3.7%), bivalent (4.9%) and bivalent unmapped (4.4%) stimuli found no reliable differences (all ps > 0.1), nor did the contrast between congruent (3.4%) and incongruent (3.7%) conditions ($p= 0.79$), nor those between congruent or incongruent and the univalent conditions, (ps > 0.09).

DISCUSSION

Bivalent unmapped stimuli were not associated with a detriment in performance relative to univalent stimuli (there was a small and non-significant difference in the opposite direction), i.e. a character that belonged to the same stimulus type as previously encountered in the context of a task but was never associated with a response did not interfere more than a character that did not belong to a category previously encountered in a task context. This makes it unlikely that the processing locus of the task-set conflict found in Experiment 5 was attentional selection. Second, in contrast to Experiment 5, there was clear evidence of response conflict: a robust effect of congruency in the RT data, as well as longer RTs for bivalent incongruent stimuli than univalent stimuli. The comparison between bivalent congruent and univalent stimuli provided no evidence of set-level conflict, as there was some facilitation on bivalent congruent trials relative to univalent trials (though it did not reach statistical significance). It is possible that response facilitation on bivalent congruent trials has masked the conflict on the task-set level (Steinhauser & Hübner, 2009).

General Discussion

The starting point for the present set of experiments was the ubiquitous finding in the task-switching ERP studies of a negative polarity switch-related potential starting at about 300 ms following stimulus onset over the parietal scalp (Karayanidis et al., 2003; Lavric et al., 2008; Nicholson et al., 2005; Rushworth et al., 2002). Like the behavioural residual switch cost, it is present even when preparation is effective (Lavric et al., 2008; Karayanidis et al., 2010); like the residual switch cost, it has been suggested to be a manifestation of task conflict (Lavric et al., 2008; Elchlepp et al., 2011). However, according to two-stage TSR (Rogers & Monsell, 1995; Rubinstein et al., 2001, Meiran, 1996) or the 'failure to engage' in TSR (De Jong, 2000) accounts, both the residual switch cost and the switch negativity could be reflections of post-stimulus TSR.

A brain potential signature of task conflict

The present investigation attempted to identify an unequivocal electrophysiological correlate of task conflict. To rule out possible effects of TSR, stimulus valence was manipulated in a design in which the task changed on a block-by-block rather than trial-by-trial basis. We examined whether our manipulation of task conflict resulted in a brain potential of the same polarity, time-course and scalp distribution as the switch versus repeat negativity in task-switching investigations. Experiment 5 did indeed identify an ERP effect of valence that had these characteristics; however, there were also two earlier effects of valence in ERP components associated with perception and attention (N1 and the Selection Negativity). Experiment 6, which controlled for perceptual, familiarity and other possible differences between the bivalent (digit-letter) and univalent (digit-symbol) stimuli from Experiment 5, showed that the differences in N1 and the Selection Negativity were present in the absence of a valence manipulation. In contrast, the longer-latency negativity in response to digit-letter relative to digit-symbol stimuli was present only in Experiment 5 (see Figures 5.7 and 5.8). These results support the interpretation of the post-stimulus switch-repeat negativity in task-switching studies as a manifestation of task conflict. Furthermore, our behavioural data (see discussion below) suggest a locus of conflict at the level of task-set, rather than response selection.

The current results are consistent with previous neuroimaging evidence of the role of task conflict, such as the demonstration with fMRI of persistence of activity that is anatomically-specific for the no longer relevant task (Wylie et al., 2004; Yeung et al., 2006) and the fact that this activity is greater after a change of task than following a task repetition (Yeung et al., 2006). The anatomical inference achievable with EEG is severely limited by the inverse problem of determining a solution in high-dimensional space (brain volume) from a low-dimensional measurement space (scalp electrodes). Hence, it is hard to determine to what extent the differential ERP negativity elicited in the present bivalent versus univalent contrast reflects activity specific to the no-longer relevant (letter classification) task, as in the above fMRI investigations. Yet, the temporal resolution achievable with brain potential measurements (such as EEG/ERPs) is far superior to that of haemodynamic and metabolic techniques (such as fMRI). Its benefit here is that it provides insight into the time-course of task conflict. In particular, it shows that the activity that most clearly differentiated between bivalent and univalent stimuli occurred immediately after the perceptual and attentional components of the ERP (e.g. N1) and well before the mean RT in the digit classification task (~600 ms) locating the onset of long-term task-set conflict that Experiment 5 measured to a time at around 300 ms.

Deconstructing task conflict

Further insights were provided by the behavioural results. Experiment 5 found little evidence of response conflict, as indicated by the absence of an effect of congruency. Longer RTs for congruent stimuli than for univalent stimuli point to conflict at the level of task-set. In the Discussion of Experiment 6, we considered whether a potential source of task-set conflict is attentional selection. This refers to the notion that persistence of attentional settings of the no longer relevant task may lead to competition for attentional selection. Another potential source of conflict is competition between task goals/criteria. This assumption implies that even partial perceptual analysis of the dimension (component) of the stimulus that is no longer relevant (e.g. letter in digit-letter compounds) may activate the irrelevant classification criterion and/or the associated categories (e.g. vowel versus consonant) whose activation competes with that of the relevant criterion (odd versus even).

Experiment 7 was designed to test behaviourally for the presence of attentional conflict following the assumption that, if conflict arises at the early stage of attention to

visual features, it should be detectable even for stimuli that contain similar features, but do not afford the categorisation rules and the associated responses- i.e. the letters that were not mapped onto responses in the letter task in Experiment 7 and were subsequently presented as part of 'bivalent unmapped' stimuli. Contrary to this prediction, Experiment 7 found no evidence of conflict elicited by bivalent unmapped stimuli relative to univalent stimuli.

It is important to note that, although the findings of Experiment 7 suggest that attentional conflict is unlikely to have caused the ERP negativity in Experiment 5, they do not rule out a contribution of attentional conflict to the residual switch cost, and, indeed, to the switch negativity in task-switching studies. As already mentioned above (see Introduction and Discussion of Experiment 5), the task-set conflict documented in Experiment 5 was driven by long-term associations between a class of stimuli (letters) and the task that was irrelevant during digit classification (letter classification), rather than by transient inertia of the letter classification task. There was more opportunity for the attentional settings of the irrelevant task to dissipate in the present paradigm compared to conventional trial-by-trial task-switching designs. Indeed, unpublished work in our laboratory using eye-tracking indicates that there is carry-over of attentional settings in trial-by-trial task switching and that it contributes to the switch cost (Longman, Lavric & Monsell, under revision). Furthermore, our recent analyses of the switch negativity with temporal PCA (Elchlepp et al., 2011) found switch –repeat differences in the Selection Negativity that were separable from the subsequent switch-induced negativity in the 300-500 ms time-range. In the present study too, the effects of valence on the Selection Negativity were somewhat larger in Experiment 5 than in the control (Experiment 6) (see Figure 5.7), but this difference did not reach statistical significance.

In the absence of conflict in attentional selection, do these results contain any clues regarding the source of set conflict in Experiment 5? In the Discussion of Experiment 5, we hypothesised that conflict could arise at the level of task goal ('classify letter'). This raises the question why there was no discernable goal-level conflict in Experiment 7. One noteworthy difference between Experiments 5 and 7 is in the tasks and categories they used. For each task in Experiment 5 (letter, digit) we used two non-arbitrary, pre-learned and well-practiced categories with multiple members and meaningful lexical labels (vowel, consonant, odd, even). The letter and digit tasks in Experiment 7 each used four ad-hoc

arbitrary single-member categories, which were not explicitly labelled (the self-generated labels were probably the names of the category members themselves- the letters). Thus, it seems likely that the 'architecture' of the task-sets in Experiment 5 contained separable category and response levels, with the category level heavily reliant on previously learned, verbally mediated representations of semantic categories (e.g. vowel, odd), and response level reliant on arbitrary mappings to buttons (fingers). Hence, conflict at the category level could occur (and perhaps be resolved) relatively independently from the response level. In contrast, the arbitrary nature of the response categories in Experiment 7 makes it less likely that the task-set would contain a level of categories separable from that of responses. This account in terms of task-set architecture could explain the robust effect of set conflict along with no discernable effect of response conflict in Experiment 5, and the converse pattern of results in Experiment 7- large congruency effects suggestive of response conflict and no (or small/undetectable) set-level conflict.

The idea that task-sets have hierarchical architecture (or structure), which has implication for task-set control and task competition is not new (cf. Kleinsorge & Heuer, 1999) and may well be the key to understanding the divergent patterns of set versus response conflict in Experiments 5 and 7. However, our experiments were not designed to examine the effect of categories used in tasks (arbitrary versus ad hoc) on task conflict. Hence, the contrast between different architectures is not well controlled in the present set of experiments: there were differences between experiments in the number of categories and responses, in whether the S-R mappings were one-to-one or many-to-one, etc. Further investigations are needed to control for these variables. Recent unpublished data from our lab (Van't Wout, Monsell, & Lavric, in preparation) from experiments that did control the above variables also point to reduced response conflict (smaller congruency effects) with classifications that rely on non-arbitrary (pre-learned) categories, relative to arbitrary categories, supporting different sources of task conflict in the two kinds of classifications.

6

The effect of switching on the Nogo N2

One surprising effect in Experiment 1 (Chapter 2) was that the 'conventional' N2 Go-Nogo effect (greater magnitude of the negative-polarity N2 peak on nogo trials) was not observed, even on task-repeat trials. Whilst this finding was incidental in the context of the attempts to determine the 'locus' of the residual switch cost it may have significant implications for the functional interpretation of the N2 effect. It may also have implications for the task-switching literature, in particular, for the issue of how the interaction between task-sets may impact on task-specific processes.

The analysis of the ERPs in the symmetry task was presented in Chapter 2 with regards to the processing of the irrelevant dimension of the stimulus- its lexical frequency, but not with regards to the task-relevant Go-Nogo factor. The present chapter presents the analysis of the symmetry task with regards to the Go-Nogo contrast, as well as a follow-up experiment that tested for the conventional Go-Nogo effects in the same (symmetry) task in the absence of task switching. The latter was needed to ascertain that the absence of a conventional N2 Go-Nogo effect in the task-switching experiment is indeed due to task-switching and not to peculiarities of the symmetry decision task.

Experiment 1: Go-Nogo contrast in the symmetry task

Experiment 1 investigated the effect of switching on word frequency in order to determine the locus of the residual switch cost in the semantic decision task. By making the symmetry task a Go-Nogo task we had hoped to use the N2 effect as a marker of completion of the symmetry judgment. In the conventional Go-Nogo paradigm, the participant is required to make a motor response to a stimulus (or a category of stimulus) and withhold the response to another stimulus (category); to ensure the 'prepotency' of the motor response, Go stimuli are typically 2-3 times more frequent than Nogo stimuli. A large corpus of studies employed this basic design to contrast the ERPs associated with Go and Nogo stimuli. Almost invariably, such studies find a robust increase in the magnitude of the N2

component (peak) of the ERP on Nogo trials, along with an increase in the longer-latency anterior P3 component (e.g. Eimer, 1993; Pfefferbaum, Ford, Weller & Kopell 1985; Lavric et al., 2004). Variations of the basic design above have included studies that replaced the overt motor response with a covert one (e.g. covert counting, Pfefferbaum et al., 1985) and studies that equated (Jodo & Kayama, 1992; Lavric et al., 2004; Pfefferbaum et al., 1985) or parametrically manipulated (e.g. Eimer, 1993; Niewenhuis et al., 2003) the frequency of Go-s and Nogo-s; for the most part, these investigations found the same basic pattern of N2-then-P3 augmentation for Nogo relative to Go stimuli.

The latencies of the N2 and P3 differences between Go and Nogo trials (the former precedes the latter by 150-200 ms at their maximum) suggest they may reflect different stages of response selection. Because we were interested in the earliest stages of response selection, we focused on the N2 enhancement on Nogo trials. There are two influential accounts of this effect. One interprets the N2 effect as a correlate of the inhibition of the response tendency (Jodo & Kayama, 1992; Eimer, 1993; Pfefferbaum et al., 1985; Falkenstein, Hoormann & Hohnsbein, 1999). The observation of the N2 effect in the absence of motor responses (Pfefferbaum et al., 1985) has been taken as an indication that N2 reflects inhibition during early stages of response selection, before motor activation (Eimer, 1993; Falkenstein et al., 1999). An alternative account of the N2 effect is that it reflects the registration of the competition between the prepotent (but inappropriate) Go response and the null response on the Nogo trials. An early variant of this account referred to this as 'response mismatch' (Mäntysalo, 1987). A subsequent, more elaborate, variant is the 'conflict monitoring' theory (Yeung, Botvinick & Cohen, 2004) developed to explain a range of neuroscientific phenomena, including the N2 modulation in the 'go-nogo' paradigm and other tasks that elicit conflicting response tendencies (e.g., Eriksen flanker paradigm, Yeung & Cohen, 2006). It posits that the anterior cingulate cortex (a likely neuroanatomical substrate of differences in N2 and the Error-Related Negativity, Nieuwenhuis et al., 2003, but see Bokura, Yamaguchi & Kobayashi, 2001; Lavric et al., 2004) monitors response conflict online and biases subsequent activity in other brain regions (e.g. lateral prefrontal cortex).

Although the inhibition and conflict monitoring accounts diverge with regards to the specific process proposed to underlie the N2 effect, according to both accounts the

hypothetical process occurs early during response selection. If this processing stage is indeed the locus of the residual switch cost, one would expect the Nogo-induced N2 enhancement to be delayed or its evolution slowed when one switches to the Go-Nogo task from another task, relative to repeating the Go-Nogo task.

METHOD

The method of Experiment 1 is described in Chapter 2.

RESULTS

Go-nogo analysis of the symmetry task

The first trial of each block, errors and trials preceded by errors were discarded from the behavioural and ERP analyses. 62.5% of trials in the symmetry task were Go trials. For those responses were slower on switch (mean = 951 ms) compared to repeat (mean = 899 ms) trials; a reliable RT switch cost of 52 ± 13 ms, $F(1, 17) = 15.61$; $p < 0.01$. For errors, a reliable switch cost ($2.6 \pm 0.8\%$), $F(1, 17) = 10.11$; $p < 0.01$, and a main effect of symmetry (Nogo vs. Go, $5.5 \pm 1.1\%$), $F(1, 17) = 25.16$; $p < 0.001$ were found, the latter reflecting more commission errors on Nogo trials (8%) than incorrect or omitted responses on Go trials (2.5%). The switch cost for omission errors was ($2.2 \pm 0.8\%$) while for commission errors it was ($2.8 \pm 1.1\%$).

ERPs

ERP waveforms for Go and Nogo trials for switch and repeat trials separately are shown in Figure 6.1.

Possible early effects of switching (150-250 ms)

The ANOVA with the factors Go-Nogo (2), switch (2), region (4; anterior frontal, posterior frontal, parietal, occipital) and laterality (left, middle, right) showed a main effect of switching, $F(1,17) = 9.48$; $p < 0.01$ and a switch by laterality interaction, $F(2,34) = 4.24$; $p < 0.05$. The amplitudes were more positive for switch than repeat trials particularly in left and central scalp regions. This likely reflects the overspill of the preparation-related switch-induced positivity into the stimulus interval.
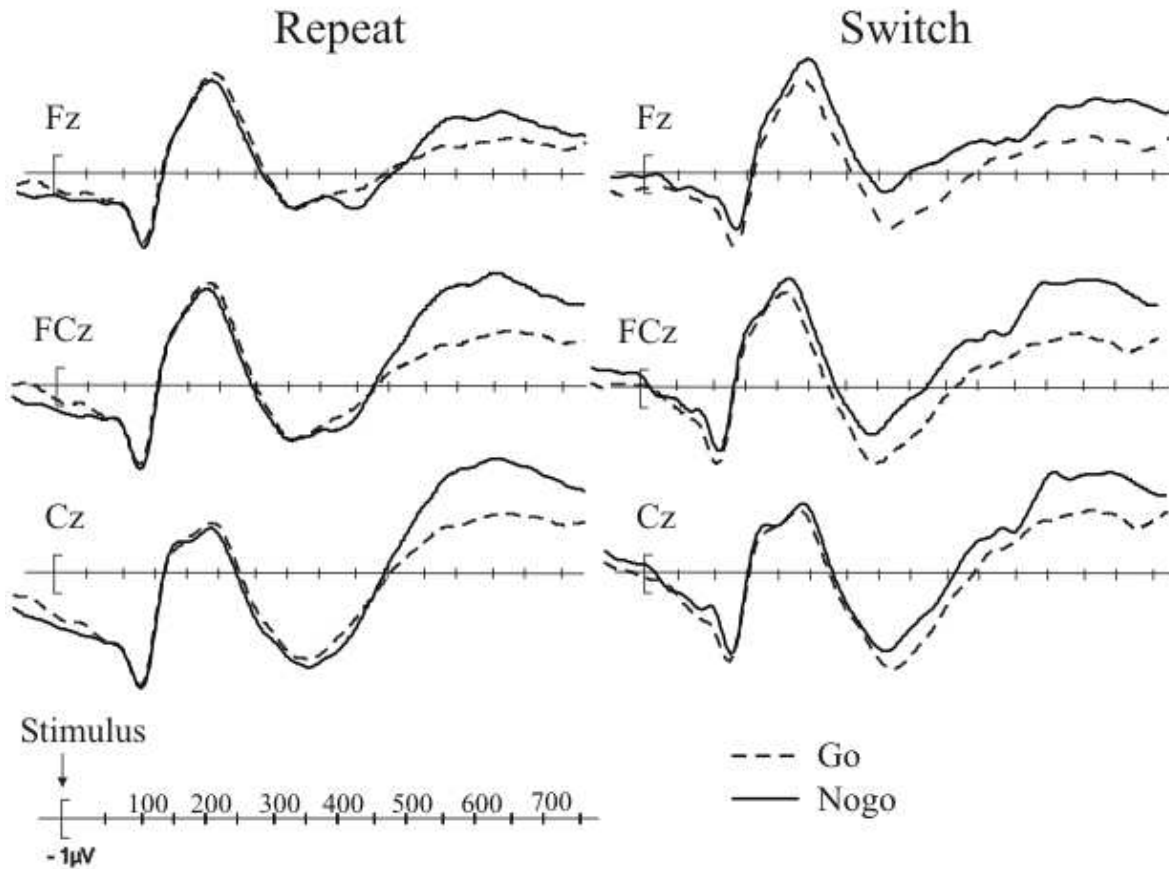
Figure 6.1 *Waveforms for Go and Nogo trials, separate for switch and repeat*

N2 time window (250-450 ms)

The ANOVA on the N2 time range included the additional factor time window (2; 250-350, 350-450 ms) and showed an interaction of Go-Nogo with region, $F(3, 51) = 15.63$; $p < 0.001$, a Go-Nogo by switch by time window interaction, $F(1,17) = 4.85$; $p < 0.05$ and a three-way interaction between Go-Nogo, time window, region and laterality, $F(6,102) = 4.18$; $p < 0.01$. Separate analysis for the two time windows showed Go-Nogo by region interactions in both (250-350 ms: $F(3, 51) = 9.90$; $p < 0.01$; 350-450 ms: $F(3, 51) = 18.60$; $p < 0.001$), a main effect of switch, $F(1,17) = 4.44$; $p = 0.05$ and a switch by Go-Nogo interaction between 350-450ms, $F(1,17) = 5.43$; $p < 0.05$. Separate ANOVAs for switch and repeat in this time-window showed a Go-Nogo by region interaction for the switches, $F(3, 51) = 4.84$; $p < 0.05$ and no reliable effects for the repeats. The Go-Nogo by region interaction for the switch condition did not reflect the expected N2 effect (N2 enhancement on no-go trials over the central anterior scalp), but a frontal positivity for switches, as

indicated by region-wise t-tests for the switch trials. The t-test for the frontal posterior central region (in which a conventional N2 should be manifested) found marginally more positive amplitudes for on Nogo trials than on Go-s, $t(17) = 2.05$, $p = 0.056$.

P3 time window (450-750 ms)

Go-Nogo interacted reliably with region, $F(3,51) = 9.41$; $p < 0.001$, laterality, $F(2,34) = 4.16$; $p < 0.05$, and region and laterality, $F(6,102) = 2.98$; $p < 0.05$. The switch by region interaction was marginally reliable, $F(3,51) = 3.68$; $p = 0.058$. A t-test on the typical P3 region, frontal posterior central confirmed a larger P3 for Nogo versus Go, $t(17) = 2.52$, $p < 0.05$, as would be expected. The factors Go-Nogo and switch did not interact in this time-window.

DISCUSSION

The analysis of the Go vs. Nogo contrast in the symmetry task in Experiment 1 did not reveal the conventional N2 effect (greater negative-polarity amplitudes for Nogo relative to Go stimuli). On the contrary, on switch trials the amplitude on Nogo trials had a more positive polarity than that on Go trials – although with a more frontal, rather than a central maximum (see difference in Fz and Cz in Figure 6.1). With regards to the Nogo P3, the results show clearly the midline P3 modulation on Nogo trials relative to Go trials.

The ERP results indicate that performing a Go-Nogo task within a task-switching design eliminated the N2 effect that is otherwise ubiquitous in Go-Nogo studies: even on trials on which the Go-Nogo task was repeated, there was no sign of an enhancement of the N2 component or a midline negativity of the same distribution at a longer latency. However, before one attributes the absence of the N2 effect to task-switching, it is important to ensure that it is not caused by the specific characteristics of the Go-Nogo task used in Experiment 1. Most Go-Nogo experiments use very simple, well practiced, perceptual discriminations and a very limited set of stimuli (often only two). Might it be that the lack of a conventional N2 Go-Nogo difference is due to the nature of the task in Experiment 1 – a non-trivial symmetry classification with a large set of stimuli? The class of stimulus may also play a role in conjunction with the required classification: outside the laboratory, one tends to extract from words semantic, rather than colour symmetry, information. Furthermore, because the mappings symmetric = Nogo and asymmetric = Go

were fixed over participants, it is conceivable that brain potential differences resulting from the processing of symmetric versus asymmetric stimuli may have masked the N2 Go-Nogo difference. The following experiment was run to address these concerns.

Experiment 8

To ensure that the symmetry task used in Experiment 1 yields a typical N2 Go-Nogo difference, in this experiment the symmetry task was run in the absence of another task (and task-switching). All within-task parameters were kept as constant as possible (stimuli, apparatus, EEG set-up) with the exception of the elements that were associated with the task-switching aspect (e.g. the task cues were removed, see Figure 6.2). The following description includes the cross-study comparison with Experiment 1 as well as two additional, post-hoc analyses that seemed necessary to draw valid conclusions.

METHOD

Participants

Eighteen students from the University of Exeter (12 female, 6 male, aged between 18 and 42) gave informed consent following the guidelines set by the University of Exeter School of Psychology ethics committee and were paid £4.- for participation.
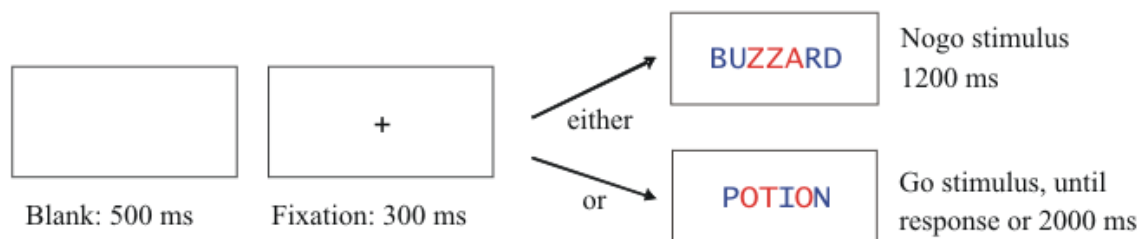

Figure 6.2 *Trial sequence and example stimuli of Experiment 8*

Stimuli and Procedure

This study used two thirds of the word stimuli from experiment 1 (256 out of 384, see Figure 6.2 for examples and differences in trial procedures between Experiment 1 and 8). In the switching experiment each stimulus was presented three times. To rotate stimuli across

participants so that a third of them saw a particular stimulus first on a switch trial, a third as a first repeat and a third as a second repeat, stimuli were divided into three groups. Within each group half of the stimuli represented a living thing, half a non-living object, half were of high and half of low word frequency, 37.5% of them were symmetrically coloured. They were further equated for word length within each group. By choosing stimuli of two of those groups for this experiment we ensured that they are a subset that has the same characteristics as the larger set of stimuli in Experiment 1.

Each trial started with a blank screen for 500 ms, followed by a fixation cross for 300 ms, which in turn was followed by the stimulus. Nogo stimuli were presented for 1200 ms; Go stimuli were presented until a response was given or (otherwise) for 2000 ms. When a response was made to the Nogo stimulus or there was no response to the Go stimulus within 2000 ms, the word "ERROR" was displayed for 1500 ms. Participants performed 4 blocks with 64 trials, each block containing 37.5% Nogo trials.

ERPs

The EEG was recorded using the same equipment and settings as experiment 1. To facilitate comparisons with the switching study the EEG was segmented into a 750 ms epoch, time-locked to the stimulus and baseline-corrected relative to the average of the 100 ms preceding the stimulus. After discarding segments with incorrect responses, remaining segments were visually inspected and those containing muscle, drift and ocular artifact rejected. The resulting EEG segments were averaged for every participant and experimental condition.

RESULTS

Behavioural results

There were more errors on Nogo trials than on Go trials: Experiment 1, Nogo 7.5%, Go 2.4%, $F(1, 17) = 26.431$; $p < 0.001$; Experiment 8, Nogo 14.5%, Go 2.6%, $F(1, 17) = 68.26$; $p < 0.001$. The overall error rate in Experiment 8 was larger (8.6%) than in Experiment 1 (5%, $F(1, 34) = 9.23$; $p < 0.01$), which was mainly due to more errors on Nogo trials, 14.5% versus 7.5%, (study x Go-Nogo interaction, $F(1, 34) = 15.1$; $p < 0.001$). RTs on Go trials were considerably longer in Experiment 1 (symmetry task only: 927 ms) compared to Experiment 8 (727 ms), $F(1, 34) = 38.0$; $p < 0.001$.

ERPs

ERP waveforms for Go and Nogo in relevant electrodes (Fz, FCz and Cz) and topographies of the Nogo minus Go differences in both experiments are shown in Figure 6.3. It can be seen that in Experiment 8 the usual modulation of N2 by Go-Nogo was present.
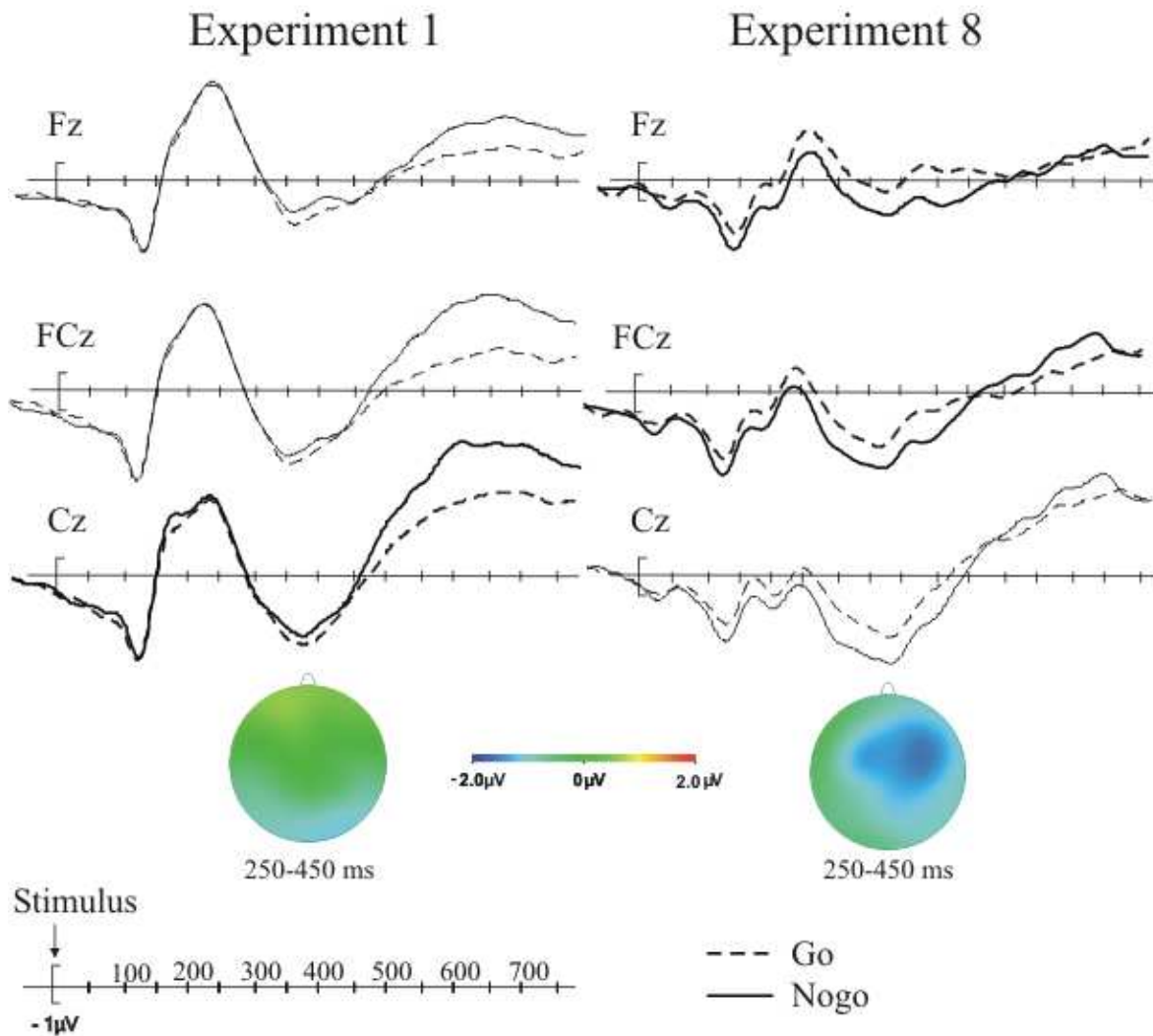
Figure 6.3 *ERPs for Go and Nogo and topographies of the Nogo minus Go difference N2 in Experiments 1 and 8*

N2

The ANOVA with the factors Go-Nogo (2), time window (2; 250-350, 350-450 ms), region (4; anterior frontal, posterior frontal, parietal, occipital), laterality (left, middle, right) and the between subjects factor study revealed a main effect of Go-Nogo, $F(1, 34) = 13.3$; $p < 0.01$, and an interaction between Go-Nogo and region, $F(3,102) = 6.04$; $p < 0.01$.

Importantly, Go-Nogo interacted with region and study, $F(3,102) = 9.53$; $p < 0.001$, and laterality and study, $F(2,68) = 3.77$; $p < 0.05$. To examine possible cross-study differences in the typical N2 region a separate ANOVA was run for the middle posterior frontal region. Here, Go-Nogo interacted with study, $F(1, 34) = 6.40$; $p < 0.05$; the N2 was larger for Nogo than Go in the study without switching, $F(1, 34) = 11.36$; $p < 0.01$, but not in the task-switching study $F(1, 34) = 0.05$; $p = .85$.

P3

For the broader peak of the P3, a wider time range was chosen so that here the factor time window had three levels (450-550, 550-650, 650-750 ms). Go-Nogo interacted with time window, $F(2,68) = 8.84$; $p < 0.01$, with region, $F(3,102) = 4.70$; $p < 0.05$, and with laterality $F(2,68) = 9.55$; $p < 0.001$. Further, there was a reliable three way interaction between Go-Nogo, region and study, $F(3,102) = 5.44$, as well as a four way interaction between Go-Nogo, time window, region and laterality $F(12,408) = 6.21$; $p < 0.001$. A separate ANOVA run for the middle posterior frontal region (capturing the typical P3 topography) showed that P3 Go-Nogo differences were slightly larger Experiment 1 compared to Experiment 8 but not reliably so, $F(1, 34) = 2.11$; $p = 0.16$.

DISCUSSION

The results from Experiment 8 show that the absence of the N2 effect in the Go-Nogo task used in Experiment 1 (with task-switching) was not due to peculiarities of the symmetry task – indeed, without task-switching this task yields a clear Nogo-induced negativity in the N2 window with the expected latency and scalp distribution. So, it appears that it is task-switching that eliminated the N2 Go-Nogo effect in Experiment 1.

One possibility, however, is that task-switching slowed all processing and that this may have delayed the onset of the Nogo-related negativity resulting in its masking by the much larger P3 effect in the ERP average. One way to examine this interpretation is to use trials on which the RTs in both studies are comparable. A simple division of trials by fast-slow RTs was not possible since there are no RTs for Nogo trials. However, we could exploit the fact that our stimuli were words and use word length as a separation criterion, that applies equally to Go and Nogo trials. Unsurprisingly, in both studies the symmetry judgement was substantially faster for short words than for long words. In the Go-Nogo

study the mean RT for 3-4 letter words was 652 ms, while for 6–7 letter words it was 744 ms. In the switching study participants responded to 3-4 letter words on average within 826 ms and to 6–7 letter words within 977 ms. When the slowest three participants were excluded and only the task repeat trials were selected the mean RT to 3-4 letter words was 762 ms for Experiment 1, which is comparable with the mean RT of 744 ms for long words in Experiment 8.

On the basis of this subset of trials we aimed to answer the following two (related) questions: (1) is a typical N2 effect present on symmetry task trials from Experiment 1 on which the required perceptual classification was easy (shortest words), as reflected in fast responses? (2) does one still find a reliable N2 modulation in Experiment 8 (no task-switching) for the trials on which perceptual classification was hard (long words), as indicated by long RTs. As in the analysis of the N2 above, a time range between 250-450ms was chosen, broken down into two time windows (250-350 and 350-450, see waveforms in Figure 6.4).

(1) The only significant effect in the ANOVA on short words in the switching study was a four-way interaction between time window, Go-Nogo, region and laterality, $F(6,84) = 2.59$; $p = 0.049$. To investigate this further, separate ANOVAs were run for the two time windows but no reliable effects were found in either. Between 350-450 ms the interaction between Go-Nogo and region approached significance, $F(3,42) = 3.31$; $p = 0.069$ but the modulation did not resemble the typical N2 effect. The amplitudes for Nogo versus Go were more negative in occipital and parietal regions, while they were more positive in anterior and central regions of the scalp.

(2) In the ANOVA for long words in the Go-Nogo study the main effect of Go-Nogo was marginally reliable, $F(1,17) = 4.18$; $p = 0.057$, along with a reliable interaction between Go-Nogo and laterality, $F(2,34) = 5.66$; $p < 0.01$. Separate analyses for left, right and central regions of the scalp revealed a reliable effect of Go-Nogo that was right lateralised, $F(1,17) = 8.43$; $p < 0.05$. For the central portion of the scalp this effect was marginally reliable, $F(1,17) = 3.99$; $p = 0.062$. Here, Go-Nogo effects differed depending on region, $F(2,34) = 3.62$; $p < 0.05$ with anterior- and posterior frontal regions showing more negative amplitudes for Nogo than Go.
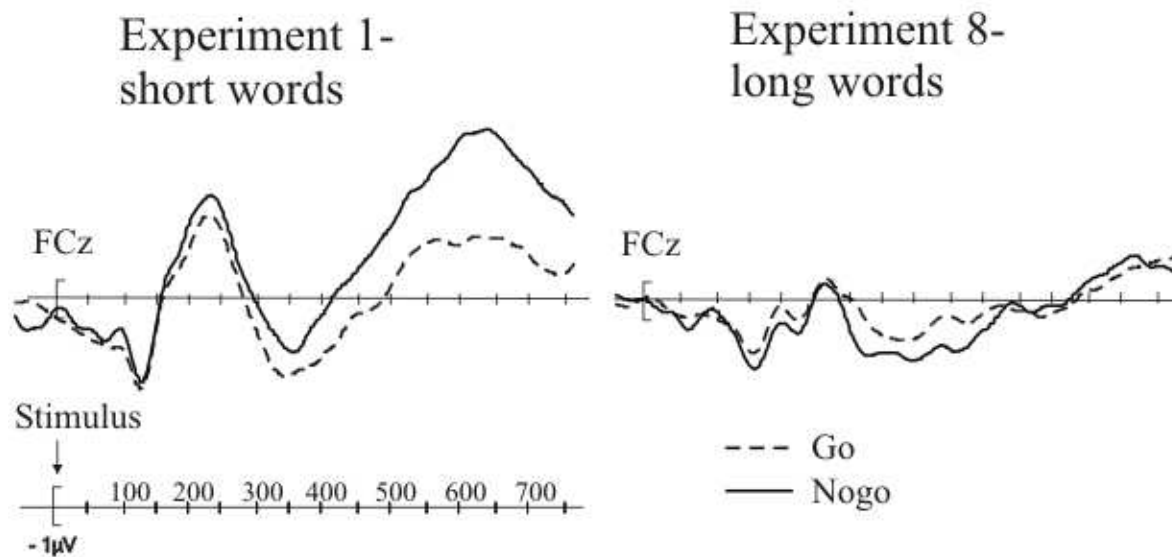
Figure 6.4 *ERPs for Go and Nogo for trials with short words (Experiment 1) and long words (Experiment 8)*

The results from these additional analyses show that even on trials with long RTs from the experiment without task-switching the N2 effect was present and that even on trials with fast responses from the task-switching experiment the effect was absent.

We now return to the two competing accounts of the N2 effect mentioned in the Introduction: (1) that the N2 difference reflects the inhibition of the prepotent response at the early stages of response selection; (2) that N2 effect is an index of the conflict monitoring operated by the anterior cingulate. The lack of an N2 effect in a task-switching context is potentially compatible with either account. The inhibition account cannot be dismissed because in the task-switching experiment in addition to the Go response in the symmetry task, there was also the competing Go response of the other task. Hence, the Go response in the symmetry task may have not been sufficiently strong (prepotent) to require inhibition on Nogo trials. In contrast, without task-switching, as in conventional Go-Nogo experiments, only one Go response was made throughout Experiment 8. If the competing response from the other task requires inhibition and such inhibition is applied, there might not be a distinction between Go and Nogo trials since inhibition is applied on both. One might be able to test this assumption by looking at Go-Nogo differences in congruent and incongruent trials, i.e. trials where there is the need to suppress the irrelevant response (incongruent) and trials where the irrelevant response is the same and where there might

even be response facilitation (congruent trials). If the assumption that inhibiting the irrelevant response abolishes the Go-Nogo N2 in a switching study is true one should find the effect present on congruent trials but abolished on incongruent trials. A subsequent analysis therefore examined whether an N2 enhancement would be present when comparing Nogo to congruent Go trials. No reliable differences were found in the typical N2 region between Go-congruent and Nogo, ($F(1,17)= 0.32$; $p = 0.6$).

General Discussion

Experiment 8 established that the symmetry task yields a clear Nogo-induced negativity with the expected latency and scalp distribution. This suggests that it is indeed the case that the demands of having to switch unpredictably on a number of trials abolished the N2 effect, even on trials when the task was repeated. To rule out that slow responses in the task- switching study were responsible for a possible masking of the N2 with the subsequent P3, an additional analysis examined trials with responses that were fast and comparable to response latencies in Experiment 8. Even on fast trials no N2 enhancement for Nogo trials was found in Experiment 1.

To distinguish between the inhibition and the conflict account of the N2 one further issue needed to be addressed. It was important to determine whether the need to suppress the irrelevant response on Go trials in the switching study resulted in response-related inhibition on both Go and Nogo trials. This could mean that the inhibition account still held, but one could not detect the inhibition via the Go-Nogo contrast in Experiment 1. The lack of an N2 on congruent Go trials on which the irrelevant response does not need to be suppressed makes the possibility that Go trials require similar inhibition to Nogo under switching conditions less likely. With regards to the conflict monitoring account, one can assume that conflict between task-sets is monitored to some extent on all trials in the switching study, even when the task repeats. In fact, Experiment 5 has documented the presence of task-set conflict even when long blocks of the same task were performed. This makes it plausible that the 'conflict detector' (in the anterior cingulate or elsewhere) was overwhelmed by the (large) conflict between task-sets and was insensitive to within task response conflict, hence the absence of N2 enhancement on Nogo trials. Further research

into the interaction between task-switching and the go-nogo paradigm will be needed in order to adjudicate between these alternatives.

7

General Discussion

This thesis begins with the question: which processes are modulated by a switch in tasks so as to result in performance decrements even when there is the opportunity to prepare for the switch? To monitor the temporal evolution of task processing a new approach was taken; tasks were chosen whose processing stages might leave a signature in the ERP. Thus, the (approximate) onset of particular stages and their further development could be examined to localise the reaction time cost of a switch to particular stages ("partition the switch cost"), by comparing ERPs on task-switch and task-repeat trials, all other things being equal. Using this technique three experiments (reported in Chapters 2 and 4) investigated the effects of a prepared switch between tasks on performance and ERPs, and one examined the effects of an unprepared switch (reported in Chapter 3). The presence of a marker of a task-related process in the ERP further enabled us to assess the extent to which that process was activated even if it was irrelevant on that trial, and how this irrelevant activation was modulated by switching. The experiments reported in Chapter 5 took the idea of conflict due to activation of elements of the irrelevant task further, examining how conflict due to the activation of the irrelevant task-set is expressed in the ERP. Successfully linking an ERP component to task-set conflict is an important contribution for subsequent investigations of when in the process of switching to a new task this conflict arises and which factors increase or decrease this conflict. Finally, Experiment 8 in Chapter 6 followed up an interesting incidental observation in Experiment 1, and confirmed that the absence of the usual ERP signature of non-go responses in that experiment could indeed be attributed to the control demands of concurrent task-switching. In the following paragraphs, I summarise the main findings (in italics) and consider their implications and possible future research.

Experiments 2-4 (Chapters 2, 3 and 4)

Prepared switching to a lexical task mainly delays or prolongs the duration of processes well before response selection. For the lexical tasks used in the experiments in Chapter 2 these processes could be pre-lexical encoding or relatively early stages of lexical access. Either is compatible with the idea of "attentional inertia": a difficulty reorienting attention to orthographic attributes, or a difficulty reactivating the lexical pathway, until the lexical task has been performed at least once.

This finding has implications for theories about the residual switch cost since it clearly emphasises an early locus of at least a major part of the effect. It is compatible with two-stage accounts of TSR such as Rogers & Monsell's (1995) suggestion that the completion of task-set reconfiguration required exogenous activation by the stimulus, and with Rubinstein et al.'s (2001) more explicit proposal that this stage involves retrieval of S-R rules into working memory since one would expect such retrieval to occur before the response is selected.

This finding is no less compatible with both task-set inertia and task-set reactivation accounts, but only if it is assumed that the elements of task-set that persist or are reactivated affect the duration of early processes. This has not been the general assumption. Proponents of task-set inertia (Allport & Wylie, 1994; Yeung & Monsell, 2003) have generally attributed the impact of task-set inertia to a slowing of response selection. Similarly Waszak et al. (2003, 2004, 2005) proposed that the effect of extra associative reactivation of a task-set on a switch trial is to prolong response-selection. Task-set inertia or reactivation are, however, compatible with the finding, if it is the orientation of attention that persists, or is associatively reactivated, in spite of preparation, more than S-R mappings.

A class of accounts that is particularly at odds with our results is the notion of response-contingent reconfiguration. Schuch and Koch (2003) proposed that even after full preparation a bivalent stimulus elicits conflict and the residual switch cost reflects task-set suppression applied during response selection to resolve the conflict. Meiran (2000; Meiran et al., 2008) further suggested that while attention may be redirected to a different dimension during preparation for a task change, a response has to be generated at least once to change the meaning of the response set (S-R weighting) to optimise performance.

Our results not only suggest an earlier locus of the major part of the residual switch cost; they also seem to suggest that there are limits to the extent to which attention can be redirected to a different dimension during the preparation interval. An attentional inertia seems to remain. This seems to pose limits to TSR and the extent to which this process can ensure flawless task performance immediately after a switch of tasks. The experiments in Chapter 2 suggest that the inability to completely redirect attention during TSR may be a major reason for this.

Future studies will also be needed to distinguish between potential forms and levels of "attentional inertia". Assuming that the spatial distribution of attention does not change, switching between the lexical and symmetry tasks in Experiments 1 could be said to require shifting attention between perceptual dimensions (letter forms and their order versus colours and their patterning), and between processing pathways (lexical access versus symmetry processing). Are these different? Is there an inertial cost associated with each level? In other cases, as in the compound stimuli of Experiments 5 and 6, the relevant perceptual features do not change (much), and performing the appropriate task requires attention to the relevant category of object (letter versus digit or symbol), and attention to the relevant response category (vowel/consonant versus odd/even). Future studies could try to distinguish the contribution of those two levels using stimuli that allow inertia of attention at only one level (e.g., single digits with odd/even and higher or lower than 5 classifications).

It would be useful to follow up the experiments in Chapter 1 with a study that distinguishes whether the delays are caused at pre-lexical (letter identification) stages or at early stages of lexical access. This could perhaps be done using a word task in which the perceptual properties of letters in the word, for example font, are manipulated. If the font discrimination was reflected in changes in early visual ERP components and if the onset of this effect was delayed one could conclude that switching delays pre-lexical processing rather than later stages such as lexical access. To investigate how we prepare for a switch to the dimension to be attended, and how this is reflected in the ERP, one could examine how the amplitudes of the posterior positivity found in the cue interval predict the delays found post-stimulus. Another important question is whether and to what extent selecting the response contributes further to the residual cost. Lateralised readiness potentials (LRPs), as

markers of response selection (stimulus-locked LRPs, s-LRPs) and preparation (response-locked LRPs, r-LRPs) seem an obvious way of examining this. If the rate of increase of the s-LRP is sensitive to response selection difficulty, then if switching tasks creates greater response selection difficulty, one might expect to see this reflected in the build up of the LRP. If one observed a delay in s-LRPs which is larger than the one measured earlier in the interval, this could give an indication of the extent to which response selection causes any extra delays. In Experiments 1 and 2 the delay measured earlier in the interval was already of the same order as the RT switch cost although it has to be acknowledged that the RT switch cost and ERP onsets of frequency and lexicality effects have standard errors around them, i.e. are only approximate estimates, which leaves some room for a contribution of response selection. However, finding the s-LRPs delayed by an amount much larger than the earlier delay would be difficult to interpret since the early delay explains the difference in RT switch cost already to a large extent. Finding the s-LRPs delayed by an amount similar to the early delay on the other hand, would not add any additional information. If a future study can replicate the finding of an early delay in task processing, and this delay represented a smaller fraction of the RT switch cost than in experiments 1 and 2, that would allow a more unambiguous investigation of possible additional delays due to response selection. So far, however, findings in Chapter 2 suggest that most of the residual cost arises at a stage before response selection. This argument, however, would be greatly strengthened if one could generalise these findings to non-lexical tasks. Experiment 4 of this thesis attempted to do this by using the emotional expression effect on ERP as a marker, but either the early locus of the switch cost does not generalise to this task (or task pair), or the EEE effect arises from an "automatic" emotion-activation process epiphenomenal to the task-specific processes required for the emotion classification task and uninfluenced by attentional inertia (See below for further consideration of the implications for processing of emotional expression.)

Another reason for looking for other cases where we can test the locus of switch effects in the same way is that, while we did our best to match the spread and distribution of spatial attention for the two tasks in Experiments 1 and 2, we cannot be sure that we succeeded perfectly in excluding shifts in the distribution of spatial attention. The absence of an early effect in Experiment 4 is reassuring in this respect, as the matching of spatial attention across tasks was surely no better here than for the lexical and symmetry tasks. It

would nevertheless be desirable to create two tasks which required attention to different dimensions of a single small stimulus and for which there were appropriate markers of dimension-specific processing.

Finally, the task pairs considered so far all involve switches between perceptual dimensions. It would be interesting to apply the same technique to task pairs requiring changes in non-perceptual dimensions (e.g. between phonology and semantics), provided suitable ERP markers could be indentified.

Evidence of processing lexical properties on trials where this dimension was irrelevant (symmetry task trials) indicated that unwanted but "automatic" lexical access occurred even when it was potentially detrimental to performance of that task. This happened more so immediately following a switch from the lexical to the symmetry task than on a second or subsequent performance of the symmetry task.
This is the first electrophysiological evidence for task-set inertia; activation and or inhibition of the task-set from the previous trial persist and interfere with performance on the current trial, particularly so on switch trials. It is consistent with Yeung et al.'s (2006) finding that switch cost correlated with fMRI activations in brain regions associated with the irrelevant task. Moreover, our finding is perhaps clearer evidence for inertia because our paradigm used trial-to-trial switching and a preparation interval sufficiently long for successful preparation (as opposed to mini blocks and a CSI of only 450 ms in Yeung et al., 2006).

This finding has implications not only for theories of the task switch cost; they can also inform theories of language processing. Whilst it seemed widely accepted that the recognition of a word, once it has been focused upon is to a large extent automatic, recent studies have questioned this assumption. Studies using the PRP paradigm investigating performance of reading aloud (Besner & Reynolds, 2006; O'Malley, Reynolds, Stolz & Besner, 2008) and lexical decision (Lien et al., 2008) suggested that lexical access is not automatic in the sense of proceeding invariantly, even with appropriate allocation of spatial attention (Besner et al., 1997). While Besner et al. concluded that sublexical phonological processing (the assembly route in dual route models) requires some form of attention whilst early orthographic processing of features and letters as well as early lexical processing does

not; Lien et al. (2008) proposed that neither lexical nor semantic activation can proceed very far without central attention. Results of Experiments 1 and 2 in this thesis suggest that lexical access occurred involuntarily on trials where it was irrelevant to the task. Lexical activation was greater after having just switched to the symmetry task compared to when the relevant task-set was more securely established, evidence that lexical access is to some degree dependent on the allocation of attention or cognitive resources, and hence influenced by inertia in that allocation. It was further found that the cognitive demands of switching away from a different task postponed or prolonged early stages of lexical access. This suggests that lexical access is not automatic in the sense of proceeding invariantly (as suggested by Besner et al.), even with appropriate allocation of spatial attention.

Future studies could investigate whether switching delayed early pre-lexical processes in visual word recognition such as letter identification, or later processes that are part of lexical access such as lexical identification and/or semantic access. With regards to the divergence between Besner's results which show attention is only needed for the sub-lexical but not the lexical route, and Lien et al.'s and our findings showing that attention is needed for lexical and semantic activations to occur, one could use the task switching procedure to determine how much attentional bias or control is needed in the lexical versus the non-lexical route. This could be done by examining the word regularity effect in prepared switching. The word regularity effect -that is faster recognition of regular than irregular words- can be taken as a measure of competition between the lexical and the sub-lexical route. While regular words are largely retrieved via the lexical route, irregular words rely more on the sub-lexical route. Switching could be used to examine which of the routes relies more on biasing or attentional resources. If the regularity effect was reduced by switching (i.e. the disadvantage for irregular words was reduced by delaying the sub-lexical route) this would support findings arguing the sub-lexical route requires more attention. Another, more subtle way of investigating whether activating the lexicon is controlled or not is to contrast the effect of switching on orthographic neighbourhood effects in a lexical decision to a semantic decision task. If the effect of switching is modulated by the type of task (e.g., neighbourhood effects could be modulated by switching for the lexical decision but not the semantic decision task) this would suggest that lexical activations are to some extent controlled.

Without the opportunity to sufficiently prepare a change to the lexical task, switching affected post-stimulus ERPs early, before markers of lexical processing were apparent. However, a clear delay of lexical processing as in the case of prepared switching could not be detected in the waveforms. The presumed ERP marker of TSR (posterior positivity for switch versus repeat) was found to be concurrent with markers of lexical processing. These results have several implications. First, they suggest that there seem to be some extra processing demands on switch trials before lexical processing can even begin. Second, they clearly demonstrate that when the switch is unprepared, TSR is not cleanly inserted as an extra processing stage on switch trials. That means that the extra processing resulting in the amplified RT switch cost seen on un-prepared switch trials did not merely prolong one or more processes in the same stage architecture as used on repeat trials, or inserts an extra processing duration. Processing was changed in a more radical way, a suggestion perhaps that a number of processes such as cue-interpretation, stimulus processing and TSR occurred concurrently with early stages of processing and that they compete for resources or result in a degradation of task-specific processing in some other way. Hence, while unprepared switching seems to alter the architecture of task processing, a prepared switch either slows processing without changing the processing architecture, or inserts an extra processing stage.

Prepared switching to an emotion categorisation task did not delay amplitudes of the emotion expression effect. The effect was still found when the emotional expression was irrelevant to the task and was not modulated by whether emotion was categorised on the previous trial or not. Similarly, the effects of letter classification were not modulated by switching, neither in the letter classification nor in the face task.
Although previous studies have attributed some contribution of automatic processes to the EEE (Kiss & Eimer, 2008) it was largely seen as a reflection of a deliberate process of forming representations of emotional content in the pre-frontal and orbito-frontal cortex (Eimer et al., 2003; Holmes et al., 2003), which was thought to require attention. Results from Experiment 4 suggest a more detailed interpretation. It appears that focusing spatial attention on the face is enough for the processes underlying the EEE to unfold. With appropriate spatial attention the emotion recognition process seems to commence automatically independent of whether the emotion classification is needed for this task or not. If the EEE does reflect automatic emotional activation for a spatially-attended face, it

is interesting that we detect no effect of attentional inertia on the time-course of this automatic process, even though one might expect less well-prepared attention to facial features on a switch trial. Perhaps it is not necessary that attention is directed to the facial features. This, and similar results for the ERP effect of the vowel-consonant distinction, suggest that some stimulus features are processed in a very efficient way (as long as spatial attention is appropriate) even if a different feature of that stimulus was attended on the previous trial. This raises the question of what is different about these features compared to those which do show "attentional inertia". Are they processed so efficiently because we are so familiar with them? Could we get rid of attentional inertia by extensive practice? Future studies should address these issues since they have important implications for people working in multi-tasking environments.

Impact of task-set interference on the ERP (Experiments 5, 6 and 7)

Task-set conflict is reflected in the ERP as a negativity ~350-450 ms post-stimulus. Consequences of attentional inertia were not detected in a paradigm where tasks switched only from block to block suggesting a short-lived nature of attentional inertia.

The post-stimulus switch negativity has been argued to be a reflection of the residual cost and the experiments in Chapter 5 provided evidence that it does indeed reflect task-set conflict. The task-set conflict related negativity we observed in a design where participants switched tasks only occasionally between long single-task blocks cannot derive from either TSR or transient task-set inertia. It must reflect relatively long tem associations between a stimulus class and the task-set. However, the behavioural effect of valence was quite small (especially after correction for differences in stimulus familiarity) and PCAs on post-stimulus ERPs often find several components that capture switch related negativities (e.g., Lavric et al., 2008 and experiments in this thesis) suggesting different processes contribute to it. The negativity found in Experiment 5 might only be a reflection of one of these. Nevertheless, the positive evidence for an associative component of interference at least establishes the plausibility of a task-conflict account of the residual cost, though in the context of a switching experiment, task-set inertia might be the major (or at least an additional) source of activation of the irrelevant task.

In conjunction with Experiments 1 and 2, the experiments in Chapter 5 also add to the discussion about attentional inertia. Experiment 7 seems to rule out that the task-set conflict in Experiment 5 had its source at the attentional level, because characters that are of the

same class (contain similar perceptual features) to those encountered in the competing task do not interfere with processing the relevant character any more than characters of a different class. In Experiment 7 responses were mapped to arbitrary categories and it was less likely that the task-set would contain a level of categories separable from that of responses; here response level conflict was strong but set-level conflict was undetected. Although informative, one should be careful drawing strong conclusions from these results. These experiments were not designed to examine the effect of categories used in tasks (arbitrary vs. well learned) on task-set conflict and hence the contrast between different architectures was not well controlled. Future investigations are needed to explore the hierarchical structure of task-sets. ERP studies could, for example, examine whether the different kinds of interference (set-level, response level) have different expressions in the ERP and how this relates to the post-stimulus negativity.

Task-switching and the no-go N2 (Experiments 1 and 8)

Switching abolished the ERP component that has consistently been linked with response conflict and/or inhibition, the N2. (Experiment 8 showed that the absence of the standard N2 in Experiment 1 was due to the requirement for task-switching, not other properties of the symmetry task employed.)

Interpretations of the N2 component in the ERP are controversial with regards to its underlying sources, with some arguing it reflects the detection of response conflict (e.g., Yeung & Cohen, 2004) and others proposing it is a reflection of response inhibition (e.g., Kopp et al., 1996). The finding that the demands of switching eliminated the N2 seems to make the inhibition account less likely since it is implausible that inhibition is not needed to successfully withhold the response in a task-switching environment.

Experiment 8 found that an N2 was present also for the most difficult (and subsequently slowest) trials. In contrast, Experiment 1 employing the switching paradigm did not find an N2 even for the easiest and fastest trials. This suggests that the lack of an N2 in this study was not due to delayed response selection. It was further explored whether the lack of an N2 enhancement in the switching paradigm was due to having to inhibit (or conflict caused by) the irrelevant response from the other task. If that was the case one would expect no enhanced N2 for incongruent trials but for congruent trials the effect should be present. This investigation found no Nogo-N2 even for congruent trials. Hence

the most likely interpretation is that the conflict detection mechanism on Go and Nogo trials is occupied dealing with conflict that arises already at the level of task-set. This finding contributes to the conflict detection theory by adding the monitoring of set-level conflict to that of response-level conflict as a function of the conflict detection mechanism.

Conclusions

This research provides strong support for a form of task-set inertia as a major source of the residual switch cost. First neurophysiological evidence for task-set inertia was found, supported by larger activations of processes employed by the irrelevant task on switch compared to repeat trials. The effect of this inertia was to modulate and delay early stages of lexical processing and these early switch induced delays were found to be substantial in relation to the RT switch cost in that task, challenging the common assumption that it is conflict at the level of response-selection that is the only or major source of the residual cost. More detail is needed on the exact amount to which early and response related processes play a role. Further, it needs to be examined whether these early effects of inertia can also be found in other, non-lexical tasks. Future studies have to establish whether inertia acts at the level of perceptual processing, i.e. is it inertia of attentional settings or does it rather modulate the first stages of task-specific processing?

Interference due to the activation of the irrelevant task-set (in this case through effects of recent training) was found to be expressed in the ERP as a posterior negativity for high versus low conflict trials even in the absence of task-switches. The successful link of this ERP component with task-set conflict allows further studies to examine which factors increase this conflict, how it can be reduced as well as whether it arises at different times under certain conditions. The presence of task-level conflict in switching studies further seemed to overshadow within-task response conflict emphasising the importance of task-level conflict in relation to processes linked with response selection.

For switching tasks to affect early lexical processing implies that reading is not as automatic as previously assumed, a finding adding to recent research in the language literature employing dual-task and attentional blink paradigms. Further, if one accepts the

dual-route account of visual word recognition, this also suggests that not only the sublexical route but also the lexical route requires attentional resources. This research illustrates that the task-switching paradigm is a useful tool to examine the amount of resources needed for visual word recognition.

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