An ERP-Approach to Study Age Differences in Cognitive Control Processes

Jutta Kray and Ben Eppinger

1 Introduction

The flexible adaptation to changes in the environment is one important feature of intelligent behaviour and is associated with the ability to efficiently control one's own processing. Cognitive control refers to the ability to guide thoughts and actions in accord with internal task goals. Controlling one's own behaviour is particularly required in situations that involve the flexible switching between multiple tasks, the selection and maintenance of task-relevant and the inhibition of task-irrelevant information, as well as the monitoring of error and conflict information (e.g. [22, 42, 47]). In this project phase we have focused on the investigation of age-related resource limitations in task switching and the inhibition of task-irrelevant information. Research in the later project phase was concerned with control processes related to the monitoring of error and conflict information (see Ferdinand et al., Error-Induced Learning as a Resource-Adaptive Process in Young and Elderly Individuals of this volume).

In this chapter, we will first review age-related resource limitations in control processes required for efficiently switching between tasks and for successfully inhibiting well-learned response tendencies. Then, we will briefly describe the paradigm that we applied to measure interactions between both types of control processes. The specific goal of our project was to identify the electrophysiological correlates of control processes during task preparation and task execution. By this we hope to gain a more fine-tuned analysis of age-related differences in cognitive control processing. In the result section, we will report the most important findings of two experiments on age-related differences in control processing. Finally, we will discuss these findings in the context of the actual control models and recent findings on age deficits in control processing.

J. Kray (✉)
Developmental Psychology Unit, Department of Psychology, Saarland University, Saarbrücken, Germany
e-mail: j.kray@mx.uni-saarland.de

M.W. Crocker, J. Siekmann (eds.), *Resource-Adaptive Cognitive Processes,*
Cognitive Technologies, DOI 10.1007/978-3-540-89408-7_5,

2 Cognitive Flexibility and Inhibition Limitations in Older Adults

2.1 Age Differences in Task Switching

One prototypical paradigm that has been used to measure the ability of the cognitive system to flexibly adapt to changing environments is the so-called task-switching paradigm (for reviews, see [33, 43]). At least one reason for its popularity is that the paradigm allows researchers to study multiple separate control processes such as task preparation, interference and switching processes within the same paradigm.

In task-switching procedures, participants are usually instructed to switch between two tasks A and B. For instance, in the one task (task A), participants are asked to respond to the meaning of words, and in the other task (task B), they are asked to respond to the colour in which the words are printed. Costs of switching between tasks can be determined by comparing performance in blocks of trials in which subjects switch between both tasks A and B (mixed-task blocks) with performance in blocks of trials in which they perform only one task A or B repeatedly (single-task blocks). A number of studies have demonstrated that reaction times (RT) are longer and error rates are larger in mixed-task blocks than in single-task blocks (e.g. [1, 2, 25]). This type of switching costs is henceforth termed general switch costs (cf. [29]) and is associated with "to be in a switch situation". General switching costs are thought to reflect control processes that are required for maintaining two task sets and for flexibly selecting between them. Costs of switching between task sets can also be determined within mixed-task blocks by comparing the performance on trials in which the task was changed (AB, BA) with the performance on trials in which the task was repeated (AA, BB). This type of costs has been termed switch costs (e.g. [48]) or specific switch costs (cf. [29]) and is thought to tap the switching process per se. So far a large variety of studies found that RTs are longer and error rates are higher in switch trials than in non-switch trials (for a review, see [43]).

There are now a number of studies that examined processing limitations of task-switching abilities in older age (for a review, see [24]; for a meta-analysis, see [55]). For theories of cognitive aging it is important to know whether age-related processing limitations occur in all kinds of cognitive processes, supporting the idea of general limitations in the speed of processing (cf. general slowing account of cognitive aging; see [31, 50]), or only in some cognitive processes, indicating process-specific limitations in the elderly. Empirical evidence so far suggests that older adults have mainly difficulties in task switching that are associated with maintaining task sets and selecting between them, that is, they show larger general switch costs than younger adults. In contrast, older adults have less difficulties in switching from one task to the other, that is, the magnitude of specific switch costs is often found to be similar in younger and older adults [7, 10, 26–29, 37, 46]. Hence, the good news is that not all cognitive control processes are limited in their functioning by old age, favouring the view of process-specific limitations of task-switching abilities in older adults.

This later view is also supported by studies using functional and structural imaging methods. For instance, Braver and colleagues [5] found that both types of switching costs were associated with neural activations in different brain regions. The magnitude of general switch costs is highly correlated with brain activity in the right anterior prefrontal cortex and the magnitude of the specific switch costs is highly correlated with brain activity in the left superior parietal cortex. This is interesting since data from functional as well as structural imaging studies suggest that age-related neural changes are most pronounced in the prefrontal cortex compared to other cortices (for reviews, see [20, 44, 45]), which is in line with the observed pattern of age differences in task switching.

2.2 Age Differences in Interference Control

Another well-known task to measure the efficiency of control processing is the Stroop paradigm [53]. This task requires maintaining a less-practised action intention (e.g. naming colours) and inhibiting a well-practised action tendency (reading words). Usually participants are presented words (i.e. red, blue, yellow and green) that are either printed in a compatible colour (the word "red" printed in "red") or in an incompatible colour (the word "red" printed in "blue") and they are instructed to name the colours. On incompatible trials the less-practised action intention (colour naming) interferes with the well-practiced action tendency of reading words. Therefore, larger RT and higher error rates can be observed on incompatible than on compatible trials, termed Stroop interference effect[1] in the following (for reviews, [35, 36]). The efficiency of the cognitive system to inhibit unwanted action tendencies is reflected in small interference effects.

Empirical evidence for age-related changes in interference control is not quite clear. A number of studies found greater Stroop interference effects for older than for younger adults [9, 12, 13, 28, 30, 52, 61], whereas a meta-analysis by Verhaeghen and De Meersman [56] did not support the view of process-specific age deficits in inhibitory processing (see also [51]). That is, larger Stroop interference effects in the elderly can also be explained by age differences in general slowing of processing speed. Thus, a further goal of this study was to contribute to this debate by specifying conditions under which age-related differences in interference control are more likely to occur.

To do this, we also varied the number of incompatible trials within a given block of trials (cf. [21, 54]). Indeed, a number of studies have shown that demands on interference control are increased when incompatible trials are less frequent. Put differently, if the cognitive system adapts to easier task conditions (high number of compatible trials within a block) in which no interference occurs and is then confronted with an incompatible trial, more resources are required to inhibit the

[1] Note that there are different ways to determine the interference effect, depending on which type of baseline condition is used for comparison.

unwanted action tendency. As a consequence, the Stroop interference effect is larger. Conversely, if the cognitive system adapts to situations in which demands on interference control are high, the Stroop interference effect is smaller [21, 54].

2.3 Interactions Between Cognitive Control Processes and Their Temporal Dynamics

The general goal of this project was to assess age-related resource limitations in adaptive behaviour, in particular, in the ability to efficiently switch between tasks and to inhibit well-learned action tendencies. Our specific goal was to examine interactions between these cognitive control processes as well as to determine their temporal dynamics. To investigate interactions between control processes, we combined the above described well-known Stroop stimuli with a cue-based task-switching paradigm. Thus, the participants in our studies were required to switch between two tasks, that is, they either had to respond to the colours (task A) or to the words (task B). Demands on cognitive control processes are largest when subjects have to switch between tasks and to inhibit the currently irrelevant action tendency. Which task they should perform in a given trial was indicated by a task cue (FAR for naming the colour (in German "Farbe") and WOR for reading the word (in German "Wort")). Subsequently, the Stroop stimulus was presented (for details, see Sect. 3). This type of paradigm has several advantages. First, it allows separating cognitive activity recruited for preparing the next task from cognitive activity recruited for executing the actual tasks. Second, it also allows separating cognitive activity for task preparation from cognitive activity required for disengaging from the previous task sets (cf. [39]).

Therefore, this type of paradigm is well suited to examine whether different kinds of brain regions are recruited for task preparation and task execution by using functional imaging methods. Indeed, MacDonald et al. [34] demonstrated a dissociation between two cognitive control functions. During the task-preparation interval (between task cue and target presentation), they found larger neural activity in the left dorsolateral prefrontal cortex (DLPFC) when subjects prepared for the less practised colour naming than for the well-practised word reading tasks. During the task-execution interval (between target presentation and the next task cue), they observed a larger neural activity in the anterior cingulate cortex (ACC) on incompatible than on compatible Stroop stimuli. On the basis of these results and other findings, it has been concluded that the DLPFC plays an important role for the active representation and maintenance of task instructions or S-R rules (e.g. [41]), while the ACC is involved in the monitoring and evaluation of conflicts (e.g. [4, 6, 36]). In general, current models of cognitive control suggest that the control of goal-directed behaviour is implemented in the brain by a distributed network with anatomically dissociable subcomponents. According to the network view, the DLPFC biases task-appropriate behaviour and the ACC corresponds to an evaluation system that indicates when more control is needed [8, 19, 23]. Because of the high spatial resolution of fMRI, this method is well suited to determine what kinds of brain regions are recruited for adapting to increased control demands.

The main goal of our project was to examine the temporal course of neural activity during task preparation and task execution when the demands on cognitive control are increased. An event-related potential (ERP) approach is particularly useful in this respect, because its temporal resolution is in the millisecond range, which allows the measurement of the time course of neuronal activity with high precision. In the first experiment, we aimed at identifying ERP-correlates of age-specific resource limitations in task preparation and inhibition processes. In the second experiment, we additionally manipulated the frequency of incompatible Stroop trials to investigate how flexible the cognitive system is in allocating control resources.

3 Methods Applied

3.1 Participants

Fourteen younger adults (mean age = 21.7 years, SD = 2.15, 6 females) and 14 older adults (mean age = 62.9 years, SD = 1.9, 6 females) participated in the first experiment. All participants indicated themselves to be healthy, having a right-hand preference, no colour blindness and no history of neurological or psychiatric problems. As often reported in the aging literature [50], we obtained no reliable age differences in a subtest of semantical knowledge, but significant differences in perceptual speed of processing, indicating the representativity of the younger and older subsample (for details, see [28]).

A subsample of participants of the first study also participated in the second experiment, 12 younger adults (mean age = 21.3 years, SD = 1.8, 6 female) and 12 older adults (mean age = 63.7 years, SD = 2.6, 6 female) (for further details, see [13]).

3.2 Procedure

The participants were presented four words (i.e. RED, BLUE, YELLOW and GREEN) whereas the display colours were either compatible or incompatible with the word meaning. The participants were instructed to perform two tasks, which will be referred to as “colour task” and “word task” in the following. In the word task, participants responded to the meaning of the word, and in the colour task to the display colour with one of the same four response keys.

In single-task conditions, the participants performed only the colour or the word task, and in mixed-task conditions, they were instructed to switch between both tasks. Which task to perform next was indicated by a task-set cue (the German letter string -wor- for the word task and -far- for the colour task).

The trial procedure was identical for single- and mixed-task blocks. Each trial started with a task-set cue (i.e. -far- or -wor-) that was presented for 500 ms, followed by a blank screen of 1,800 ms (see Fig. 1). Before the target (the Stroop word), a fixation cross was displayed for 200 ms. Then, the target stimulus was presented for 300 ms, followed by a blank screen until the response was made. ERPs were recorded in a task-cue interval, in which the subjects prepared for the upcoming task, and in a target interval, in which responses to Stroop stimuli had to be given.

Fig. 1 The trial procedure

Stimuli, tasks and trial procedure were identical in the first and the second experiment. In the first experiment, the number of incompatible trials in a block was 50%. In the second experiment, we additionally manipulated the frequency of incompatible trials within a block that was either high (80% of the trials) or low (20% of the trials).

3.3 Data Recordings

We used an IBM compatible computer for registration of reaction times (RTs) and errors and a CTX 17-inch colour monitor with a black background for stimulus presentation. Responses were registered using external response buttons.

EEG and EOG activities were recorded continuously (Neuroscan Synamps and Scan 4.2 acquisition software) from 64 tin electrodes (10–10 system) using an elastic cap (Electrocap International). We used the left mastoid as reference and the right mastoid as an active channel. The EEG and EOG signals were online bandpass filtered (DC – 70 Hz, 50 Hz notch filter) and digitized at 500 Hz. Impedances were kept below 5 kΩ (for details, see [13, 28]).

4 Results

In this section, we will report the most important findings of two experiments on age-related changes in cognitive control processes and discuss them in the context of previous findings. At first we report the behavioural results and then the ERP results.

4.1 Behavioural Results

Consistent with a number of previous findings (e.g. [25, 29, 37]; for a review, see [24]; for a meta-analysis, see [55]), we found an age-related increase in general switch costs and no age differences in specific switch costs. We also found that age differences in general switch costs were more pronounced in the word reading than colour naming task (see Fig. 2). This finding is consistent with others that demonstrated that the magnitude of switch costs depends on the dominance of a well-practised task relative to a less-practised task. For instance, Allport et al. [1], using Stroop stimuli in a task-switching paradigm, found that switching to the well-learned task (here the word naming task) results in greater switching costs. Thus, it appears that older adults have more problems to efficiently switch between tasks when word processing needs to be inhibited in the previous trial than younger adults do.

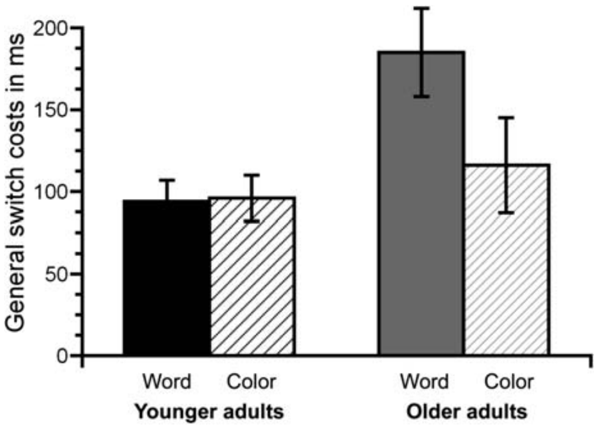

Fig. 2 General switch costs (latencies in ms) as a function of age group (younger and older adults) and task (word and colour task). Error bars refer to the standard error of the mean (SE)

As noted earlier, we were specifically interested in the interaction among cognitive control processes (see Sect. 2.3). Interestingly, our results showed that the Stroop interference effect was larger when subjects had to switch between tasks compared to when subjects were required to perform only one task in a block (e.g. [59]). Thus, subjects are less efficient in interference control when the demands on cognitive control are increased, that is, when participants have to switch between tasks. However, we did not find interactions with age.

Also in line with findings of a meta-analysis [56], results of our first study indicated that age differences in the Stroop interference disappeared when age differences in general speed were controlled.[2] This finding suggests that there are no age-specific resource limitations in interference control. However, age differences in interference control might occur when demands in control processing are increased. Therefore, we increased the demands on interference control by varying

---

[2] Age differences in interference effects were no longer significant on the basis of proportional scores (incompatible/compatible), which take age differences in baseline performance (here: latencies in compatible trials) into account, only on the basis of difference scores (incompatible – compatible).

the frequency of incompatible trials in our second study. Consistent with previous studies, we found larger interference effects when the frequency of conflict trials was low (see Fig. 3; cf. [21, 54]). Hence, subjects were less adapted to conflict when the frequency of incompatible trials was low and had to engage more in conflict monitoring when an infrequent incompatible trial occurred. Of most relevance for the second study was the fact that age differences in the Stroop interference effect were influenced by the frequency manipulation. Older adults showed larger interference effects than younger adults when the frequency of conflict trials was low (see Fig. 3). This effect was only found for the colour naming task, but not for the word reading task, and was significant even after controlling for the effects of general slowing, that is, on the basis of proportional scores. Hence, there is evidence for age differences in the Stroop interference effect, but it is limited to situations of high demands on interference control.

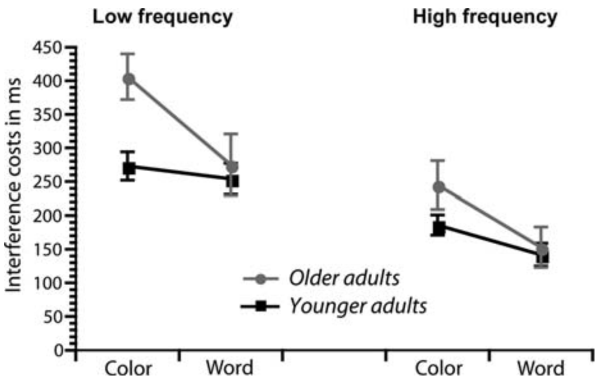

Fig. 3 Interference costs (latencies in ms) as a function of age group (younger and older adults) and task (word and colour task) and low (*left side*) and high frequency of incompatible trials (*right side*). Error bars refer to the standard error of the mean (SE)

4.2 ERP-Results

ERP data will be reported in two sections. In the first section we report analyses of neural activity that is related to preparatory processes and the ERPs were averaged time-locked to the onset of task-cue presentation (see Fig. 1). In the second section we report analyses of neural activity that is related to target processing and response execution. Thus, the ERPs were averaged time-locked to target and response onset. We will primarily review results on age-related changes in ERP correlates of task preparation and inhibitory processes.

4.2.1 Age Differences in ERP Correlates of Task-Preparation Processes

The analysis of task-cue related neural activity indicated age-related changes in two ERP components: in the P300 and in a contingent negative slow wave (CNV). Figure 4 displays ERP grand averages in the task-cue interval at three central electrodes elicited in single- and mixed-task blocks separately for younger and older adults aggregated across the colour naming and word naming task. For all conditions a large positive component, the P3, was evoked at parietal electrodes for younger and older adults. Towards the end of the task-cue interval, a CNV emerged at central recording sites for the mixed relative to single-task blocks in the older age group.

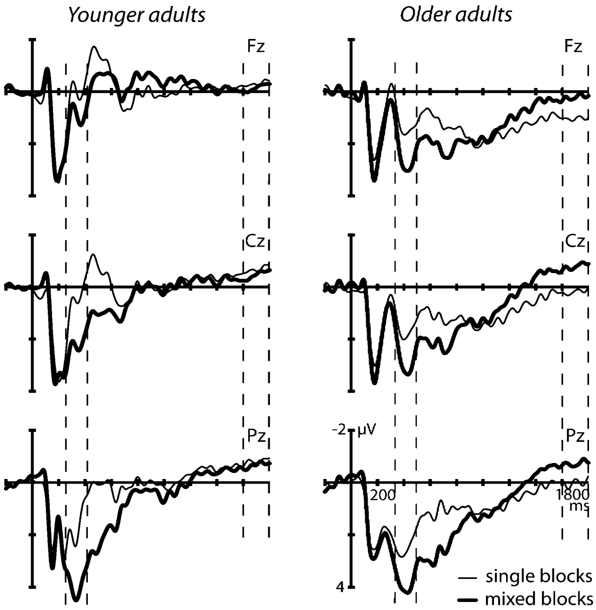

Fig. 4 Grand average ERPs in the cue interval for single (*thin line*) versus mixed-task (*thick line*) blocks separately for younger and older adults aggregated across tasks at the three midline electrodes (FZ, CZ and PZ). The *vertical bars* indicate cue onset, tick spacing in the x-axis is 200 ms, and the broken lines indicate the time windows that were used for statistical analysis of the P300 and CNV

The first noteworthy finding was a parietally distributed P300 was evoked by task cues that was larger under switching conditions (i.e. in mixed-task blocks) than non-switching conditions (i.e. in single-task blocks), which is consistent with other findings (e.g. [59]). Generally, the P300 is assumed to reflect processes that encode and update the currently relevant task context (e.g. [11, 38]). In the present study, the P300 presumably reflects the updating of task sets for the word or colour task. Age-related changes in this component are primarily related to the P300 latency that is significantly slowed in the older group and under switching conditions. Age-related slowing of P300 peak latency is a well-replicated finding in the area of cognitive aging; however, most studies focused on age differences in the implementation of attentional control as measured with the Oddball paradigm (for a review, see [49]).

In contrast to the age effects for P300 peak latency, we found no reliable age effect in the P300 amplitude. Most obvious was that the P300 amplitude was substantially larger for switching conditions in both tasks. Although we found no age-related changes in the P300 amplitude, the topography of the P300 was significantly modulated by age but only in the word task. In the word task, in which general switch costs were also higher for older adults, the P300 topography took the form of a more flattened anterior–posterior distribution. Specifically, we found a loss of the centro-parietal focus in the older age group. Age-related changes in the topography of the P300 peak amplitude of similar kinds have been reported in other ERP studies on cognitive aging (e.g. [17]). The functional and neuroanatomical factors contributing to the modified P300 topography in the elderly are still a matter of debate. However, we suggest that the flattened P300 topography and the enhanced general switch costs in the word task reflect that older adults may recruit frontal areas to a larger extent for the more demanding implementation of the task set of the word task (cf. [40]).

A second important finding of our study is that we found age-related changes in the CNV. The CNV is assumed to be associated with the ability to maintain task-set representations over time. In the present study, no reliable CNV differences between single and mixed blocks were obtained for younger adults (see Fig. 4). In contrast, older adults showed a substantially larger CNV under switching conditions, suggesting that they were differentially engaged in the maintenance of task sets in mixed compared to single task blocks. If we take the CNV as an indicator of the ability to actively maintain task-set representations over time, then the findings suggest that older adults have problems in maintaining the currently relevant task set under mixed-task conditions (but see [59]; for an alternative interpretation, see [28]).

In our second study we investigated age differences in the flexibility of resource-adaptive behaviour by manipulating the degree of interference during task performance. It was expected that in blocks with a low frequency of incompatible trials, control demands on task preparation are decreased whereas demands on conflict monitoring are increased, and vice versa. However, age effects in the ERP correlates of task preparation did not interact with the frequency manipulation (for other effects of the frequency manipulation, see [13]).

4.2.2 Age Differences in ERP Correlates of Interference Control

The analyses of ERP components in the target interval allowed us to examine age-related differences in interference control during target processing and response execution. Findings from several recent ERP studies suggest that stimulus-driven inhibitory control is reflected in a negativity for incompatible Stroop trials (which will be termed Ni in the following). This component has been assumed to reflect early conflict detection (e.g. [32, 59, 60]). A second negativity occurs during response execution on incompatible Stroop trials, which is called correct response negativity (CRN).

Results of our first experiment showed that Ni latency was slower for the colour naming than the word reading task, which is consistent with a greater behavioural Stroop interference in the colour naming than in the word reading task (see Fig. 2).

Moreover, the Ni was substantially slowed for older than for younger adults. Age effects were even more pronounced in the colour naming task when subjects had to switch between tasks, thus when control demands were increased. Furthermore, consistent with a number of other findings (e.g. [32, 60]), we obtained a larger Ni amplitude for incompatible than for compatible trials. However, this effect was clearly present in both age groups and in both tasks, supporting the view that the Ni component reflects general conflict processing that is required whenever a target stimulus involves ambiguous information (e.g. [32, 60]). Thus, it appears that the Ni reflects a general mechanism of early conflict detection that is relatively invariant across tasks and age. Hence, we only found evidence that conflict detection in slowed in the elderly.

In contrast, results of both studies provided evidence for age-related differences in response-related conflict processing. For younger adults, a negativity (CRN) was obtained that was larger for incompatible than for compatible trials. As no such compatibility effect was found for older adults, this can be taken as evidence for age differences in response-related conflict processing. Hence, it appears that younger adults are better able than older adults to discriminate between incompatible and compatible trials at a response-related processing stage. A similar negative deflection, termed Error-related Negativity (ERN, [18]) or Error negativity (Ne, [14]), peaking around 80 ms after the response, is often observed in erroneous responses and has been considered as a part of a more general executive control system that monitors for conflicts and errors. The attenuation of the Ne in older adults [15, 16, 19] has been taken as evidence for a lower flexibility of error and action monitoring in the elderly. Even though more research is required to elucidate the functional processes reflected in the CRN, the present results of age differences in the CRN suggest, similar to the ERN/Ne, age-related changes of the action monitoring system.

Results of our second study replicated and extended this result, that is, we found a larger CRN for incompatible than for compatible trials only for the younger adults (see also [57, 58]). Furthermore, the compatibility effect in the CRN for younger adults was sensitive to the probability manipulation, i.e. it was larger when incompatible trials were less frequent (see Fig. 5). This pattern of results in the CRN amplitudes parallels the behavioural Stroop interference effect that was larger when demands on conflict processing were increased (see Fig. 3). This finding also suggests that younger adults are able to adjust their behaviour depending on the task context, which means that they are well prepared for conflict when incompatible trials are frequent and less prepared when conflict is decreased and incompatible trials are rare.

Our results are also consistent with recent findings from a study of Bartholow and colleagues [3], who manipulated the frequency of incompatible trials in the Eriksen Flanker task. They also found that the CRN was sensitive not only to response conflict, but also to conflict that emerges, when expectancies about the compatibility of the target stimulus were violated.

In contrast to younger adults, older adults did not show reliable differences in the CRN between conditions, with enhanced amplitudes, independently of the

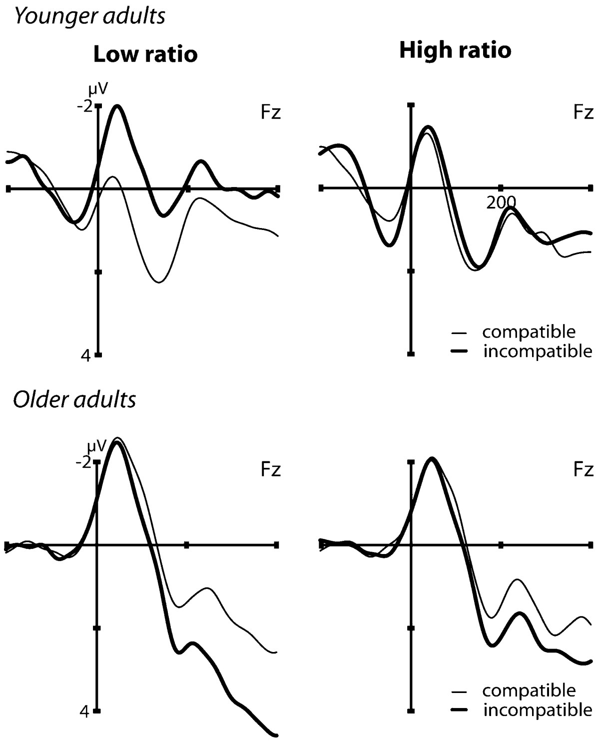

Fig. 5 Grand average ERPs in the response interval for compatible (*thin line*) vs. incompatible (*thick line*) correct trials separately for younger and older adults as a function of low versus high frequency (ratio) of incompatible trials at FZ. The *vertical bars* indicate response onset, and tick spacing in the x-axis is 200 ms

frequency manipulation. Thus, older adults were not able to flexibly adapt to changes of conflict demands. The finding that the CRN did not differentiate between compatible and incompatible trials in the older age group confirms the findings of our first study and suggests impairments of older adults in discriminating compatible from incompatible trials. Our data are also consistent with findings from Gehring and Knight [19]. They found that CRNs were enhanced for patients with frontal lobe lesions. Gehring and Knight [19] suggested that these patients might suffer from an impaired representation of the contextually appropriate stimulus response mapping, and by this, are not able to distinguish between what was a correct response and what was not. Applying this argumentation to older adults, it is conceivable that in highly demanding task situations older adults suffer from a compromised representation of the actually relevant task set (and thus the correct response) even on compatible trials, leading to conflict when the actual response is matched with the impaired representation. As a consequence, they are not able to build up expectancies about the compatibility of the target stimulus, which might explain the absence of a frequency effect in the older age group.

5 Summary and Conclusions

In sum, the results of our studies have implications on current theories of cognitive aging and provide a number of new theoretical insights in the field of age-related resource limitations of adaptive behaviour.

First, the behavioural data of the two studies suggest, in line with previous findings [29, 37], that age-related resource limitations primarily occur when older adults have to select and maintain task-relevant information, thus at a general level of switching between task sets. In contrast, older adults have no problems when they have to reconfigure tasks on a trial-to-trial basis, thus at a specific level of task switching. Moreover, in the first study we did not find evidence for age-related impairments in the ability to inhibit irrelevant action tendencies, which is also in line with previous findings [56]. The new behavioural findings of our studies are that older adults have even greater difficulties in task-set selection when they are switching to a well-learned activity (the reading task) that was strongly inhibited in the previous trial. Moreover, older adults have more difficulties in inhibitory processing than younger adult do, when demands on interference control are increased (i.e. when incompatible trials are less frequent and therefore less expected).

Second, we identified two ERP components that varied with switching demands during task preparation, the P300 and the CNV. The P300 is thought to reflect processes related to encoding and updating of task-relevant information (e.g. [11, 38]). The P300 latency was increased in the elderly, especially in mixed-task blocks, indicating that older adults are slowed in the updating of task-relevant information when they have to switch between tasks. The P300 amplitude elicited by the task-set cue was larger for mixed-task blocks than for single-task blocks with a parietal maximum in the younger group and a broader distribution in the older group in the word task. This finding suggests age-related deficits in updating of currently relevant tasks, primarily when switching from a less-practised task is required. Furthermore, only older adults showed an enhanced CNV under switching conditions, suggesting that older adults have problems to maintain task-relevant information over time.

Third, results of our studies also identified two ERP components that varied with inhibitory demands, an early negativity related to the processing of conflicting task information (termed Ni; cf. [32, 60]), and a late negativity related to response-related processing (termed CRN; see [57, 58]). The Ni is thought to reflect conflict detection when the target stimulus contains ambiguous information. The latency of this component was substantially increased for the colour naming than the word reading task under switching conditions and this difference varied with age. Thus, older adults were much slower than younger adults in conflict detection when demands on cognitive control were increased. Although the Ni was larger for incompatible than for compatible trials [32, 60], the Ni amplitude did not vary across tasks and age, suggesting no qualitative changes in conflict processing in the elderly and for different task domains. Furthermore, the response-related negativity on correct trials (CRN) was found to be larger for incompatible than compatible Stroop stimuli. However, this was only the case for the younger age group, whereas the CRN occurred on both types of trials in the older group. Moreover, the compatibility effect in the

CRN varied as a function of conflict ratio in younger but not in older adults, which points to the view that older adults are impaired in the flexible adaptation to changing demands on conflict processing. As the CRN has been considered to reflect the efficiency of the conflict monitoring system [3, 19], results of our studies suggest that the older adults were less efficient in discriminating between incompatible and compatible trials at a response-related processing stage and by this showed resource limitations in action monitoring as well as in flexibly adapting to changes of conflict demands.

Taken together, our findings are inconsistent with the view that cognitive aging is mediated by a single, global mechanism that affects all type of cognitive processes such as a general age-related decline in speed of information processing. Instead, our findings support the view of age-specific resource limitations in cognitive control processing. On the behavioural level, we found age-related resource limitations in maintaining and selecting between task sets and in inhibitory processing when the demands on cognitive control were high. This view was further confirmed by age-related differences in ERP correlates of task-preparation and inhibitory processing. Age-related slowing was observed for task-set updating and conflict detection. Age-specific processing limitations were obtained during task-set maintenance and response-related conflict processing, as well as in the flexibility adaptation to conflict demands. Generally, the ERP-approach seems to be a useful tool for obtaining a detailed view on age differences in cognitive control processing.

Acknowledgments This research was supported by the Deutsche Forschungsgemeinschaft (grant SFB 378, EM 2). We wish to thank Oliver John and Barbara Mock for their support during data collection and Axel Mecklinger for very helpful comments.

References

1. Allport, D.A., Styles, E.A., Hsieh, S. Shifting intentional set: Exploring the dynamic control of tasks. In C. Emilia, M. Moscovitch (Eds.), Attention and Performance XV (pp. 421–452). Cambridge, MA: The MIT Press (1994).
2. Allport, D.A., Wylie, G. Task-switching, stimulus-response bindings, and negative priming. In S. Monsell, J. Driver (Eds.), Control of Cognitive Processes: Attention and Performance XVIII. Cambridge, MA: MIT Press (1999).
3. Bartholow, B.D., Pearson, M.A., Dickter, C.L., Sher, K.J., Fabiani, M., Gratton, G. Strategic control and medial frontal negativity: Beyond errors and response conflict. Psychophysiology, 42:33–42 (2005).
4. Botvinick, M., Braver, T.S., Barch, D.M., Carter, C.S., Cohen, J.D. Conflict monitoring and cognitive control. Psychological Review, 108:624–652 (2001).
5. Braver, T.S., Reynolds, J.R., Donaldson, D.I. Neural mechanisms of transient and sustained cognitive control during task switching. Neuron, 39:713–726 (2003).
6. Carter, C.S., Braver, T.S., Barch, D.M., Botvinick, M.M., Noll, D., Cohen, J.D. Anterior cingulate cortex, error detection, and the online monitoring of performance. Science, 280:747–749 (1998).
7. Cepeda, N.J., Kramer, A.F., Gonzales De Sather, J.C.M. Changes in executive control across the life span: Examination of task-switching performance. Developmental Psychology, 37:715–730 (2001).

8. Cohen, J.D., Botvinick, M., Carter, C.S. Anterior cingulate and prefrontal cortex: Who's in control? Nature Neuroscience, 3:421–423 (2000).
9. Comalli, P.E.J., Wapner, S., Werner, H. Interference effects of Stroop color-word test in childhood, adulthood, and aging. Journal of Genetic Psychology, 100:47–53 (1962).
10. DiGirolamo, G.J., Kramer, A.F., Barad, V., Cepeda, N.J., Weissman, D.H., Milham, M.P., et al. General and task-specific frontal lobe recruitment in older adults during executive processes: A fmri investigation of task-switching. Neuroreport, 12(9):2065–2071 (2001).
11. Donchin, E., Coles, M.G. Is the P300 component a manifestation of context updating? Behavioral and Brain Sciences, 11:357–427 (1988).
12. Dulaney, C.L., Rogers, W.A. Mechanisms underlying reduction in Stroop interference with practice for young and old adults. Journal of Experimental Psychology: Learning, Memory and Cognition, 20:470–484 (1994).
13. Eppinger, B., Kray, J., Mecklinger, A., John, O. Age differences in task switching and response monitoring: Evidence from ERPs. Biological Psychology, 75:52–67 (2007).
14. Falkenstein, M., Hohnsbein, J., Hoormann, J., Blanke, L. Effects of errors in choice reaction tasks on the ERP under focused and divided attention. In C.H.M. Brunia, A.W.K. Gaillard, A. Kok (Eds.), Psychophysiological Brain Research (pp. 192–195). Tilburg: Tilburg University Press (1990).
15. Falkenstein, M., Hoormann, J., Hohnsbein, J. Changes of error-related ERPs with age. Experimental Brain Research, 138:258–262 (2001).
16. Falkenstein, M., Hoormann, J., Hohnsbein, J. Inhibition-related ERP components: Variation with modality, age, and time-on-task. Journal of Psychophysiology, 16:167–175 (2002).
17. Friedman, D., Kazmerski, V., Fabiani, M. An overview of age-related changes in the scalp distribution of P3b. Electroencephalography and Clinical Neurophysiology, 104:498–523 (1997).
18. Gehring, J.W., Goss, B., Coles, M.G., Meyer, D.E., Donchin, E. A neural system for error detection and compensation. Psychological Science, 4:385–390 (1993).
19. Gehring, J.W., Knight, R.T. Prefrontal cingulate interactions in action monitoring. Nature Neuroscience, 3:516–520 (2000).
20. Hedden, T., Gabrieli, J.D.E. Insights into the ageing mind: A view from cognitive neuroscience. Nature Neuroscience Reviews, 5:87–96 (2004).
21. Jacoby, L.L., Lindsay, D.S., Hessels, S. Item-specific control of automatic processes: Stroop process dissociations. Psychonomic Bulletin and Review, 10:638–644 (2003).
22. Jonides, J., Smith, E.F. The architecture of working memory. In E.D. Rugg (Ed.), Cognitive Neuroscience. Studies in Cognition. Cambridge, MA: MIT Press (1997).
23. Kerns, J.G., Cohen, J.D., Mac Donald, A.W., Cho, R.Y., Stenger, V.A., Carter, C.S. Anterior cingulate conflict monitoring and adjustments in control. Science, 303:1023–1026 (2004).
24. Kramer, A.F., Kray, J. Aging and divided attention. In E. Bialystok, F.I.M. Craik (Eds.), Lifespan Cognition: Mechanisms of Change. New York: Oxford University Press (2006).
25. Kray, J. Task-set switching under cue-based and memory-based switching conditions in younger and older adults. Brain Research, 1105:83–92 (2006).
26. Kray, J., Eber, J., Karbach, J. Verbal self-instructions in task switching: A compensatory tool for action-control deficits in childhood and old age? To appear in: Developmental Science, 11:223–236 (2008).
27. Kray, J., Eber, J., Lindenberger, U. Age differences in executive functioning across the lifespan: The role of verbalization in task-preparation. Acta Psychologica, 115:143–165 (2004).
28. Kray, J., Eppinger, B., Mecklinger, A. Age differences in attentional control: An event-related potential approach. Psychophysiology, 42:407–416 (2005).
29. Kray, J., Lindenberger, U. Adult age differences in task switching. Psychology and Aging, 15:126–147 (2000).
30. Li, K.Z.H., Bosman, E.A. Age differences in Stroop-like interference as a function of semantic relatedness. Aging, Neuropsychology, and Cognition, 3:272–284 (1996).
31. Lindenberger, U., Mayr, U., Kliegl, R. Speed and intelligence in old age. Psychology and Aging, 8:207–220 (1993).

32. Liotti, M., Woldorff, M.G., Perez III., R., Mayberg, H.S. An ERP study of the temporal course of the Stroop color-word interference effect. Neuropsychologia, 38:701–711 (2000).
33. Logan, G.D. Executive control of thought and action: In search of the wild homunculus. Psychcholological Science, 12:45–48 (2003).
34. MacDonald III, A.W., Cohen, J.D., Stenger, V.A., Carter, C.S. Dissociating the role of the dorsolateral prefrontal and anterior cingulate cortex in cognitive control. Science, 288:1835–1838 (2000).
35. MacLeod, C.M. The stroop task: The 'gold standard' of attentional measures. Journal of Experimental Psychology: General, 121:12–14 (1992).
36. MacLeod, C.M., MacDonald, P.A. Interdimensional interference in the Stroop effect uncovering the cognitive and neural anatomy of attention. Trends in Cognitive Sciences, 4:383–391 (2000).
37. Mayr, U. Age differences in the selection of mental sets: The role of inhibition, stimulus ambiguity, and response-set overlap. Psychology and Aging, 16:96–109 (2001).
38. Mecklinger, A., Ullsperger, P. P3 varies with stimulus categorization rather than probability. Electroencephalography and Clinical Neurophysiology, 86:395–407 (1993).
39. Meiran, N. Reconfiguration of processing mode prior to task performance. Journal of Experimental Psychology: Learning, Memory, and Cognition, 22:1423–1442 (1996).
40. Milham, M.P., Erickson, K.L., Banich, M.T., Kramer, A.F., Webb, A., Wszalek, T., et al. Attentional control in the aging brain: Insights from an fMRI study of the Stroop task. Brain and Cognition, 49:277–296 (2002).
41. Miller, E.K., Cohen, J.D. An integrative theory of prefrontal cortex function. Annual Review of Neuroscience, 24:167–202 (2001).
42. Miyake, A., Friedman, N.P., Emerson, M.J., Witzki, A.H., Howerter, A., Wager, T.D. The unity and diversity of executive functions and their contributions to a complex "frontal lobe" task: A latent variable analysis. Cognitive Psychology, 41:49–100 (2000).
43. Monsell, S. Task switching. Trends in Cognitive Sciences, 7:134–140 (2003).
44. Raz, N. Aging of the brain and its impact on cognitive performance: Integration of structural and functional findings. In F.I.M. Craik, T.A. Salthouse (Eds.), Handbook of Aging and Cognition (2nd Ed., pp. 1–90). Mahwah, NJ: Lawrence Erlbaum (2000).
45. Raz, N. The aging brain observed in vivo: Differential changes and their modifiers. In R. Cabeza, L. Nyberg, D. Park (Eds.), Cognitive Neuroscience of Aging: Linking Cognitive and Cerebral Aging (p. 400). New York: Oxford University Press (2005).
46. Reimers, S., Maylor, E.A. Task switching across the lifespan: Effects of age on general and specific switch costs. Developmental Psychology, 41:661–671 (2005).
47. Ridderinkhof, K.R., van den Wildenberg, W.P.M., Segalowitz, S.J., Carter, C.S. Neurocognitive mechanisms of cognitive control: The role of prefrontal cortex in action selection, response inhibition, performance monitoring, and reward-based learning. Brain and Cognition, 56:129–140 (2004).
48. Rogers, R.D., Monsell, S. Costs of a predictable switch between simple cognitive tasks. Journal of Experimental Psychology: General, 124:207–231 (1995).
49. Polich, J. Meta-analysis of P300 normative aging studies. Psychophysiology, 33:334–353 (1996).
50. Salthouse, T.A. The processing-speed theory of adult age differences in cognition. Psychological Review, 103:403–428 (1996).
51. Salthouse, T.A., Meinz, E.J. Aging, inhibition, working memory, and speed. Journals of Gerontology: Psychological Sciences, 50B:P297–P306 (1995).
52. Spieler, D.H., Balota, D.A., Faust, M.E. Stroop performance in healthy younger and older adults and in individuals with dementia of the Alzheimer type. Journal of Experimental Psychology: Human Perception and Performance, 22:461–479 (1996).
53. Stroop, J.R. Studies of interference in serial and verbal reactions. Journal of Experimental Psychology, 18:643–662 (1935).

54. Tzelgov, J., Henik, A., Berger, J. Controlling Stroop effects by manipulating expectations for color words. Memory and Cognition, 20:727–735 (1992).
55. Verhaeghen, P., Cerella, J. Aging, executive control, and attention: A review of metaanalyses. Neuroscience and Biobehavioral Reviews, 26(7):849–857 (2002).
56. Verhaeghen, P., De Meersman, L. Aging and the Stroop effect: A meta-analysis. Psychology and Aging, 13:120–126 (1998).
57. Vidal, F., Burle, B., Bonnet, M., Grapperon, J., Hasbroucq, T. Error negativity on correct trials: A reexamination of available data. Biological Psychology, 64:265–282 (2003).
58. Vidal, F., Hasbroucq, T., Grapperon, J., Bonnet, M. Is the 'error negativity' specific to errors? Biological Psychology, 51:109–128 (2000).
59. West, R. The effects of aging on controlled attention and conflict processing in the Stroop task. Journal of Cognitive Neuroscience, 16:103–113 (2004).
60. West, R., Alain, C. Age related decline in inhibitory control contributes to the increased Stroop effect observed in older adults. Psychophysiology, 37:179–189 (2000).
61. West, R., Baylis, G.C. Effect of increased response dominance and contextual disintegration on the Stroop interference effect in older adults. Psychology and Aging, 13:206–217 (1998).