Available online at www.sciencedirect.com
ScienceDirect
Biological Psychology 75 (2007) 52–67
BIOLOGICAL PSYCHOLOGY
www.elsevier.com/locate/biopsycho

Age differences in task switching and response monitoring: Evidence from ERPs

Ben Eppinger *, Jutta Kray, Axel Mecklinger, Oliver John

Department of Psychology, Saarland University, Im Stadtwald, D-66041 Saarbrücken, Germany

Received 21 July 2005; accepted 7 December 2006
Available online 23 January 2007

Abstract

This study investigates age differences in the flexible adaptation to changing demands on task switching and conflict processing. We applied a cued task-switching version of the Stroop task and manipulated the ratio of conflict trials. During task preparation, the P300 varied as a function of conflict ratio and a later positive component was larger for switch than non-switch trials. Stimulus-related conflict processing as indicated by a negativity for incompatible trials (Ni) was delayed for older adults. Moreover, the Ni varied as a function of conflict ratio and was larger for switch than for non-switch trials. Age differences were also obtained in the correct response negativity (CRN). CRN was larger on incompatible trials and this CRN-compatibility effect was enhanced when incompatible trials were infrequent in younger, but not in older adults. Our findings suggest impairments of older adults primarily in response-related conflict processing and in the flexible adaptation to changing task contexts.

Keywords: Age differences; Response monitoring; Task switching; Conflict processing; ERP; Stroop task

Flexible adaptation to a rapidly changing environment presupposes a system that continuously monitors external and internal states and uses this information to guide behavior in a way that optimal adaptation is possible. In everyday life, we have to flexibly adjust and control our behavior, especially in a context in which a specific response tendency is predominant (e.g., driving on the right side) over another (e.g., driving on the left when visiting Great Britain).

Generally two sets of control processes can be distinguished: one area of research has focused on the investigation of control processes that implement task-appropriate behavior. Such control processes include the selection, updating and maintenance of task-relevant information, the switching between these task sets, and the coordination and scheduling of two or more tasks (for reviews, see Ridderinkhof et al., 2004; Smith and Jonides, 1999). A second area of research was primarily interested in the investigation of control processes that monitor task-appropriate behavior such as conflict monitoring (Botvinick et al., 2001; Yeung et al., 2004), error detection, and feedback processing (e.g., Holroyd and Coles, 2002).

Several groups of researchers have shown that older adults are impaired in most, but not in all of these cognitive control functions (for a review, see Kramer and Kray, 2006). For instance, it has been demonstrated that older adults are disproportionately impaired in maintaining and selecting task sets, whereas they show less deficits in switching between them (e.g., Kray and Lindenberger, 2000; Kray et al., 2004; Mayr, 2001). There are fewer studies that examined age differences in the monitoring of behavior. Results of these studies suggested that older adults show deficits in evaluative control functions, especially during internal and external error processing (Band and Kok, 2000; Falkenstein et al., 2001; Nieuwenhuis et al., 2002).

Further evidence for a dissociation of control components has been provided by neuroimaging studies. Several fMRI studies have demonstrated that neuronal activity in the dorsolateral prefrontal cortex (dlPFC) is increased when the demands on the representation and maintenance of task goals or response rules are enhanced which points to the important role of the lateral PFC in the implementation of control. In contrast, neuronal activity in another brain region, the anterior cingulate cortex (ACC), is increased when monitoring and evaluation of conflict is required (e.g., MacDonald et al., 2000; Kerns et al., 2004).

The main goal of this study was to examine how younger and older adults adjust goal-directed behavior depending on a task

* Corresponding author. Tel.: +49 681 3023698; fax: +49 681 3023871.
E-mail address: eppinger@mx.uni-saarland.de (B. Eppinger).

0301-0511/$ – see front matter © 2006 Elsevier B.V. All rights reserved.
doi:10.1016/j.biopsycho.2006.12.001

context that is associated with changing demands on conflict processing. Generally, we were interested in whether the efficiency of control processes associated with the implementation of task-appropriate behavior (task goals and response rules) as well as the monitoring of response outcomes is influenced by the task context. We manipulated the task context by varying the probability of specific events (the ratio of conflict to non-conflict trials) to occur in a given situation. Specifically, we asked the question whether older adults might be less able than younger adults to monitor changes in the demands on conflict processing, on the one hand, and to adjust control processing depending on that task context, on the other hand. An efficient monitoring of changes in the task context (the ratio of conflict trials) should enable participants to build up expectancies about the probability of a certain trial type and to adjust performance by engaging in the implementation of control according to these expectancies. When these expectancies are violated (e.g., when a non-conflict trial is expected and a conflict trial occurs), additional conflict will be produced that calls for adjustments in the implementation of control.

Similar to a previous study (Kray et al., 2005) we used an ERP approach to examine age differences in control processes in separate phases of a task-switching paradigm: during task preparation, when task-appropriate behavior needs to be implemented, and during task execution, when performance is monitored (Kray et al., 2005; cf. West, 2004). To investigate ERP correlates of age differences in these processes we applied a cued task-switching version of the Stroop task, which allowed us to separate control processes during task preparation (in the cue-target interval) and task execution (in the target interval). The participants were instructed to respond either to the color of Stroop words (color task) or the word meaning of Stroop words (word task). Stroop words were either compatible (e.g., blue displayed in blue color) or incompatible (e.g., blue displayed in red color) and we manipulated the ratio of compatible to incompatible trials (80% compatible and 20% incompatible, or vice versa). Furthermore, in one condition participants were asked to only perform one task during a block of trials (single-task condition) and in the other condition to switch between tasks (mixed-task condition) depending on a task-set cue.

A large number of studies have shown that performance is worse under mixed- than under single-task conditions (termed general switch costs), and on switch compared to non-switch trials (termed specific switch costs) (for reviews, see Monsell, 2003; Rubin and Meiran, 2005). General switch costs have been found to be larger for older than for younger adults, whereas the evidence for age differences in specific switch costs is rather scarce (for reviews, see Kramer et al., 1999; Kramer and Kray, 2006). General switch costs have been suggested to reflect the more global ability to effectively maintain and coordinate task sets (e.g., Kray and Lindenberger, 2000), whereas specific switch costs probably include more transient processes of task-set reconfiguration (see Rogers and Monsell, 1995) as well as interference from previous stimulus–response mappings (task-set inertia) (see Allport et al., 1994).

Moreover, in a wealth of studies participants have been found to be slower and less accurate on incompatible compared to compatible Stroop trials (termed interference costs). Although there is evidence for age-related increases in interference costs (e.g., Davidson et al., 2003; Dulaney and Rogers, 1994), results of a meta-analytic approach did not provide substantial evidence for age differences in interference costs after controlling for age differences in general speed of processing (cf. Verhaeghen and De Meersman, 1998). Interference costs have been proposed to reflect the suppression of currently inappropriate response tendencies and tend to be larger, when the word rather than the color information has to be ignored (Stroop, 1935; for a review, see MacLeod and MacDonald, 2000). Moreover, interference costs seem to be also sensitive to the proportion of conflict trials, being larger when the proportion of conflict trials is low, compared to when it is high (Jacoby et al., 2003; Tzelgov et al., 1992).

Fewer studies have investigated age differences in ERP modulations during task switching and conflict processing. Recent studies that focused on the ERP correlates of age differences in general switch costs (Kray et al., 2005; West, 2004) suggest that the P300 component is associated with the implementation of task-sets during task preparation. In these studies P300 amplitude was larger under mixed- than single-task conditions and P300 latency was longer in mixed- than single blocks for older adults. The P300 component has been suggested to reflect the updating of currently task-relevant information or task sets (Donchin and Coles, 1988), a process that is more engaged under switching conditions and delayed in older adults. Age differences in the P300 component have usually been investigated using Oddball paradigms (Friedman et al., 1997; Frodl et al., 2000). Results of these studies suggest that while younger adults show a parietal maximum of the P300 during categorization of target stimuli, older adults show a more equally distributed P300 across the scalp. On the basis of these findings it has been argued that older adults continue to use frontal lobe mechanisms even for stimuli that should have already been well encoded and/or categorized (Friedman et al., 1997).

Several recent studies have tried to identify the ERP correlates of task switching (Miniussi et al., 2005; Moulden et al., 1998; Rushworth et al., 2002). Results of these studies seem to converge on one major modulation during task-set preparation that involves a sustained positivity for switch compared to non-switch trials over parietal recording sites. This preparatory component has been assumed to reflect the strategic anticipatory reconfiguration during switch trials (Kieffaber and Hetrick, 2005) or enhanced attentional selection requirements (Rushworth et al., 2002). It is typically followed by a stimulus-locked negativity for switch compared to non-switch trials (Karayanidis et al., 2003; Kieffaber and Hetrick, 2005; Rushworth et al., 2002), which has been suggested to reflect either task-set interference or control processes during task-set reconfiguration (for a discussion, see Karayanidis et al., 2003; Rushworth et al., 2002). With respect to the control processes during performance monitoring (in the target interval), recent studies found modulations of two components, a negativity to incompatible trials (Ni) at around 350–450 ms after target onset and a negativity to incompatible trials immediately after the

response, the correct response negativity (CRN). The stimulus-related negativity to incompatible Stroop trials (Ni) has been obtained in a variety of studies using manual Stroop tasks (e.g., Kray et al., 2005; Liotti et al., 2000; West and Alain, 2000a; West, 2004). In contrast to the fronto-central N2 component that is typically found using Go-Nogo- and Stop-Signal paradigms (see Falkenstein et al., 2002; Kok et al., 2004) the Ni shows a longer latency and a more parietal distribution. However, it remains to be established, whether these components indeed reflect different processes. ERP studies that examined age differences in the Ni (West and Alain, 2000a; West, 2004) found that the component is reduced in amplitude for older adults (West, 2004; West and Alain, 2000a), suggesting that there is an age-related decline in the efficiency of stimulus-related conflict processing. However, in our previous study (Kray et al., 2005), the Ni was only delayed for older adults, but did not differ in amplitude between younger and older participants.

Instead, we found age differences in the amplitude of the CRN, a response-related component that shares the temporal and topographical characteristics of the error-related negativity (ERN/Ne) but is elicited by correct responses (see Vidal et al., 2000, 2003). The CRN was larger after incompatible than compatible Stroop stimuli in younger adults, whereas older adults showed a CRN on incompatible as well as compatible trials, suggesting age-related impairments in the monitoring of (post-) response conflict. Support for the view that the CRN is associated with response-related conflict monitoring processes also comes from a recent study of Bartholow et al. (2005). They found a larger CRN on conflict trials in the Eriksen flanker task and also showed that the CRN seems to reflect the conflict that occurs when an expectation about the compatibility of the target stimulus is violated, suggesting that the CRN might be also sensitive to conflict on the more general level of response strategies.

1. The present study

The flexible adaptation to changes in the environment is a prerequisite for successful goal-directed behavior. Older adults have been suggested to be impaired in these processes especially under high demands on cognitive control. The main goal of the current study was to determine whether age differences in ERP correlates associated with the implementation of task-appropriate behavior and response monitoring are influenced by a task context that is associated with changing demands on conflict processing. Using a cued task-switching version of the Stroop paradigm, we manipulated the task context by varying the ratio of incompatible to compatible Stroop trials. In one experimental condition, the ratio of incompatible to compatible trials was 80:20 (i.e., HI ratio condition), and in the other condition, the ratio of incompatible to compatible trials was 20:80 (i.e., LI ratio condition).

A number of behavioral studies have shown that the demands on conflict processing depend on the task context (Jacoby et al., 2003; Tzelgov et al., 1992). A task context in which incompatible trials are infrequent (LI ratio condition) leads to larger interference costs, that is, demands on conflict processing are increased. In contrast, a high ratio of conflict trials (HI ratio condition) leads to smaller interference costs, which means, that the demands on conflict processing are decreased. The monitoring of the task context seems to enable participants to build up expectancies about the probability of a certain trial type and to use this probability information to adjust performance by engaging in the implementation of control according to these expectancies. In the LI ratio condition compatible trials are more expected than incompatible trials. Therefore, conflict is enhanced when an incompatible trial occurs and this expectation is violated. In contrast, in the HI ratio condition, processing is adapted to the frequently appearing incompatible trials and conflict is not enhanced because the occurrence of incompatible trials is expected.

Consistent with the results from several studies (e.g., Kray and Lindenberger, 2000; Kray et al., 2004; Mayr, 2001), we expected older adults to show larger general switch costs than younger adults, whereas we did not expect age differences in specific switch costs. Adjustments to the task context were expected to show up in the P300 component during task preparation. Under LI ratio conditions larger P300 components were expected, because the task context called for a stronger engagement in task-set updating in order to adapt to increased conflict in the LI ratio condition. Based on recent findings (Kieffaber and Hetrick, 2005; Miniussi et al., 2005; Moulden et al., 1998; Rushworth et al., 2002), we also expected the anticipatory configuration during task switching to be reflected in a positive modulation at parietal recording sites for switch compared to non-switch trials, whereas stimulus-related effects of task-set interference should be reflected in a stimulus-locked negativity for switch compared to non-switch trials.

Interference costs as well as age differences in interference costs were expected to be increased in the low ratio condition, since demands on conflict processing were enhanced (Jacoby et al., 2003; Tzelgov et al., 1992). On the basis of previous findings (West and Alain, 2000a; West, 2004), we further expected the negativity for incompatible trials (Ni) in the target-locked averages to be increased on conflict trials, whereas it remains an open issue whether the Ni is also influenced by the task context. The CRN, in contrast, was assumed to be affected not only by response conflict, but also by the conflict that arises when an expectation is violated (Bartholow et al., 2005). Thus, the CRN should be increased on incompatible trials (response conflict) and when an expectation about the compatibility of the target is violated. As in our previous study (Kray et al., 2005), we predicted CRNs for both compatible and incompatible trials in the older age group, whereas it is an open question whether older adults are able to adjust their performance depending on the task context.

2. Method

2.1. Participants

Twenty-six adults participated in the study. The experimental procedure lasted about 3 h and the subjects received 22.5€ for participation. All participants already took part in a previous similar ERP study so that they

were highly familiar with the EEG setting and the experimental tasks (for details, see Kray et al., 2005). One younger and one older adult had to be excluded from data analyses because of problems during the acquisition of the EEG data.

The effective sample consisted of 12 younger adults (*mean age* = 21.3 years, S.D. = 1.8, 6 females) and 12 older adults (*mean age* = 63.7 years, S.D. = 2.6, 6 females). All participants indicated themselves to be healthy, having a right-hand preference, no color blindness, and no history of neurological or psychiatric problems.

The participants performed two psychometric tests, one from the domain of fluid intelligence (the Digit-Symbol Substitution test; adapted from Wechsler, 1982) and one from the domain of crystallized intelligence (the Spot-a-Word test; adapted from Lehrl, 1977) (for details, see Kray et al., 2005). A typical pattern of age effects was obtained: younger adults reached a substantially higher score ($M = 60$, S.D. = 7.7) than older adults ($M = 49$, S.D. = 9.0) on the Digit-Symbol Substitution test, $F(1, 22) = 9.5$, $p < .005$, suggesting age-related decline in perceptual speed of processing. In contrast, older adults reached higher scores in the Spot-a-Word test ($M = 28$, S.D. = 3.3) than younger adults ($M = 25$, S.D. = 3.3, $F(1, 22) = 4.5$, $p < .05$), indicating age-related increase in semantical knowledge.

2.2. Stimuli and tasks

The stimulus set of the experimental task consisted of four words (i.e., RED, BLUE, YELLOW, and GREEN). The display colors of the four words were either compatible or incompatible with the word meaning. The stimuli were presented in uppercase 48-bitmap fonts on the centre of the screen against a black background.

The participants were instructed to perform two tasks, which will be referred to as 'color task' and 'word task' in the following. In the word task, participants responded to the meaning of the word and in color task to the display color with one of the same four response keys. The participants responded with the index fingers to BLUE (left key press) and YELLOW (right key press) and with the middle fingers to RED (left key press) and GREEN (right key press).

Under single-task conditions the participants performed only the color or the word task, whereas under 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 color task).

2.3. Procedure

At the beginning of the experiment, all participants filled out an informed consent and a short demographic questionnaire. An initial practice phase served to remind participants of the response assignments. It consisted of a color-task block in which only neutral stimuli were presented (i.e., colored letters ''XXXX'') and one word-task block in which the four uncolored words were presented.

The experimental phase consisted of 32 blocks, 16 single-task blocks (8 color-task blocks, 8 word-task blocks) and 16 mixed-task blocks. The order of blocks was random with the constraint that two single-task blocks (one color and one word block) and two mixed-task blocks were grouped together. In half of the blocks the ratio of incompatible to compatible trials was low (20:80; LI ratio condition). In the other half of the blocks the ratio of incompatible to compatible trials was high (80:20; HI ratio condition). Half of the participants received the LI blocks first, and the other half performed the HI blocks first. Block order was constant across subjects and trial order was random. Each block consisted of 40 trials, yielding a total of 32 blocks × 40 trials = 1280 trials. Single- and mixed-task blocks consisted of an equal number of response types (left index, left middle, right index, and right middle) and mixed-task blocks included an equal number of color and word tasks as well as an equal number of non-switch and switch trials.

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 1800 ms. Before the target (the Stroop word), a fixation cross was displayed for 200 ms. The fixation cross served to avoid strategy effects in the color task in which the participants can reduce the interference effects by focusing their attention away from the word meaning. Thus, the entire cue-target interval lasted 2500 ms. The target stimulus was presented for 300 ms, followed by a blank screen until the response was made. After each experimental block, participants received feedback about mean response times and percentage of errors. All participants were told to respond as quickly and accurately as possible.

In sum, the experimental design consisted of the four within-subjects factors Trial type (single, non-switch, switch), Task (Color, Word), Compatibility (compatible, incompatible), and Ratio (LI, HI).

2.4. Data recording

2.4.1. Behavioral data

An IBM compatible computer was used for collecting reaction times (RTs) and errors. The stimuli were presented on a CTX 17-in. color monitor with a black background. Responses were registered using external response buttons. The experiment was controlled by the Software package Experimental Run Time System (ERTS, Beringer, 2000).

2.4.2. Electroencephalogram (EEG) recording

EEG and EOG activity were recorded continuously (Neuroscan Synamps and Scan 4.2 acquisition software) from 64 tin electrodes (10–10 system) using an elastic cap (Electrocap International). The left mastoid was used as reference and the right mastoid was recorded as an active channel.[1] The EEG and EOG signals were online bandpass filtered (DC—70 Hz, 50 Hz notch filter) and digitized at 500 Hz. Vertical and horizontal EOG was recorded from two electrode pairs placed on the infra- and supraorbital ridges of the right eye and on the outer chanti of the two eyes. Impedances were kept below 5 kΩ. To increase S–R ratio, the EEG data were offline low-pass filtered with 30 Hz prior to statistical analyses. Since low frequency drifts contaminated the EEG data in the target interval, data in this interval was additionally high-pass filtered at .5 Hz.

2.5. Data analysis

2.5.1. Behavioral data

Responses faster than 180 ms and slower than 3000 ms were excluded from data analysis. RT data were transformed using the natural logarithm of the raw data. This was done because the interpretation of age differences based on difference scores is less informative and the obtained age by condition interactions can also be explained by age differences in the baseline performance (cf. Kliegl et al., 1994, see Kray et al., 2005). The analyses of variance (ANOVA) were based on log-transformed RTs of correct responses and on errors rates. The means of log-transformed RTs, raw RTs, and error rates are displayed as a function of Trial type, Ratio, Task, and Compatibility in Table 1a (younger adults) and Table 1b (older adults).

2.5.2. ERP-data

ERP epochs were extracted off-line for three events: cue-locked activity, target-locked activity, and response-locked activity. Cue-locked ERPs were computed for each subject at all recording sites, with epochs extending from 200 ms before cue onset until 1800 ms. Target-locked ERPs were measured from 200 ms before target onset until 1300 ms; and response-locked ERPs were measured from 200 ms before response onset until 600 ms. Only correct trials entered the analysis. Since the manipulation of the ratio of conflict trials leads to an unequal number of trials in each condition in the target interval, the trial number was matched afterwards for each condition and subject. We randomly selected 30 trials in each condition and subject. However, this was not possible for non-switch and switch trials, therefore we used the maximum trial number in these conditions (at least 15 trials). Prior to averaging, trials containing eye-movement artifacts or other artifacts were excluded from further

[1] Due to problems during data acquisition in two subjects, the right instead of the left mastoid was used as reference.

Table 1
Mean (S.D.) for RTs, log-transformed RTs, and percent error scores for younger adults (a) and older adults (b)

Trial type	Ratio	Task	Compatibility	RT	log-RT	Error (%)
(a)						
Single trial	Low	Color	Compatible	560 (79)	6.293 (.131)	1.88 (1.34)
	Low	Color	Incompatible	777 (124)	6.598 (.151)	4.38 (5.34)
	Low	Word	Compatible	574 (84)	6.318 (.137)	1.95 (2.05)
	Low	Word	Incompatible	745 (113)	6.556 (.142)	5.63 (5.24)
	High	Color	Compatible	576 (100)	6.315 (.147)	1.25 (1.69)
	High	Color	Incompatible	689 (129)	6.482 (.159)	3.47 (2.43)
	High	Word	Compatible	600 (91)	6.364 (.136)	1.46 (1.29)
	High	Word	Incompatible	691 (99)	6.492 (.129)	5.76 (6.78)
Non-switch trial	Low	Color	Compatible	594 (110)	6.342 (.155)	1.20 (1.68)
	Low	Color	Incompatible	898 (159)	6.731 (.184)	8.33 (7.98)
	Low	Word	Compatible	604 (106)	6.363 (.151)	.85 (1.13)
	Low	Word	Incompatible	879 (144)	6.713 (.149)	6.64 (9.54)
	High	Color	Compatible	616 (143)	6.374 (.185)	.00 (.00)
	High	Color	Incompatible	844 (161)	6.666 (.159)	9.27 (7.52)
	High	Word	Compatible	645 (125)	6.426 (.157)	3.14 (5.38)
	High	Word	Incompatible	817 (202)	6.635 (.205)	8.13 (12.55)
Switch trial	Low	Color	Compatible	594 (99)	6.351 (.144)	1.48 (1.89)
	Low	Color	Incompatible	892 (194)	6.722 (.187)	8.90 (7.96)
	Low	Word	Compatible	606 (125)	6.361 (.168)	1.03 (1.38)
	Low	Word	Incompatible	922 (213)	6.757 (.213)	11.06 (11.13)
	High	Color	Compatible	647 (143)	6.418 (.178)	.64 (1.57)
	High	Color	Incompatible	863 (193)	6.682 (.172)	11.59 (8.81)
	High	Word	Compatible	674 (155)	6.460 (.171)	1.58 (3.08)
	High	Word	Incompatible	838 (178)	6.664 (.176)	11.89 (12.05)
(b)						
Single trial	Low	Color	Compatible	787 (99)	6.632 (.119)	1.18 (1.03)
	Low	Color	Incompatible	1112 (141)	6.697 (.129)	3.54 (2.49)
	Low	Word	Compatible	822 (99)	6.669 (.113)	1.39 (1.14)
	Low	Word	Incompatible	1001 (189)	6.855 (.166)	2.29 (3.10)
	High	Color	Compatible	825 (160)	6.668 (.179)	.63 (1.55)
	High	Color	Incompatible	979 (152)	6.837 (.158)	2.99 (2.34)
	High	Word	Compatible	827 (103)	6.681 (.118)	1.88 (2.85)
	High	Word	Incompatible	928 (137)	6.784 (.136)	1.53 (1.50)
Non-switch trial	Low	Color	Compatible	854 (157)	6.705 (.160)	.46 (.87)
	Low	Color	Incompatible	1300 (150)	7.121 (.122)	6.20 (7.05)
	Low	Word	Compatible	892 (133)	6.747 (.133)	.83 (1.05)
	Low	Word	Incompatible	1211 (152)	7.047 (.130)	5.17 (10.66)
	High	Color	Compatible	914 (194)	6.766 (.158)	.00 (.00)
	High	Color	Incompatible	1209 (223)	7.041 (.165)	5.57 (3.98)
	High	Word	Compatible	1016 (217)	6.868 (.187)	.30 (1.03)
	High	Word	Incompatible	1156 (151)	6.990 (.122)	3.43 (3.17)
Switch trial	Low	Color	Compatible	865 (143)	6.722 (.149)	1.11 (1.87)
	Low	Color	Incompatible	1315 (221)	7.132 (.173)	6.63 (8.71)
	Low	Word	Compatible	928 (154)	6.784 (.148)	.45 (1.19)
	Low	Word	Incompatible	1257 (204)	7.074 (.158)	5.83 (10.11)
	High	Color	Compatible	910 (170)	6.763 (.155)	.24 (.83)
	High	Color	Incompatible	1198 (172)	7.037 (.137)	8.63 (7.04)
	High	Word	Compatible	979 (182)	6.832 (.154)	.23 (.80)
	High	Word	Incompatible	1198 (188)	7.027 (.149)	4.63 (3.77)

analysis using a threshold criterion (standard deviations greater than 30 μV within a sliding window of 200 ms). Remaining vertical and horizontal eye movements were corrected using a modified version of the linear regression approach developed by Gratton et al. (1983), as it is implemented in the software EEProbe (ANT Software).

In case of significant interactions involving the electrode and age group factors, additional ANOVAs were conducted using amplitude-normalized data (McCarthy and Wood, 1985). Only interactions that remained significant after rescaling are reported. Whenever necessary the Greenhouse–Geisser correction was applied (Greenhouse and Geisser, 1959). In these cases the original F-value, the adjusted p-values, and the Epsilon values (ε) are reported. Additionally we report effect sizes (partial eta squared, η^2), which reflect the proportion of variance that is accounted for by the experimental manipulations (see Cohen, 1973). If not specified otherwise, the significance level in the post hoc comparisons was adjusted by means of a modified Bonferroni procedure (see Keppel, 1991).

3. Results

3.1. Behavioral data

3.1.1. Reaction time data

The ANOVA on log-transformed latencies included the factors Age group (young, old), Trial type (single, non-switch, switch), Ratio (low, high), Task (color, word), and Compatibility (compatible, incompatible). The factor Trial type was defined by two contrasts. In the first contrast, mean RTs in single trials were tested against mean RTs in non-switch trials (general switch costs), and in the second contrast, mean RTs in non-switch trials were tested against mean RTs in switch trials (specific switch costs).

The results revealed that older adults responded much slower than younger adults, Age group: $F(1, 22) = 45.97$, $p < .0001$, $\eta^2 = .68$. Generally, subjects responded much slower on non-switch than on single trials, General switch costs: $F(1, 22) = 115.85$, $p < .0001$, $\eta^2 = .84$, and slower on switch than on non-switch trials, Specific switch costs: $F(1, 22) = 6.37$, $p < .02$, $\eta^2 = .22$ (see Fig. 1a and b). Furthermore, we found a significant interference effect, that is, latencies were slower on incompatible than on compatible trials, Compatibility: $F(1, 22) = 332.45$, $p < .0001$, $\eta^2 = .94$.

General switch costs were larger on incompatible ($M = 174$ ms, S.D. = 95 ms) than on compatible trials ($M = 71$ ms, S.D. = 88 ms), General switch costs × Compat-Compatibility: $F(1, 22) = 61.58$, $p < .0001$, $\eta^2 = .74$, and were also larger when the ratio of incompatible trials was high rather than low, General switch costs × Ratio: $F(1, 22) = 8.07$, $p < .01$, $\eta^2 = .25$ (see Fig. 1b).

Moreover, we obtained a significant interaction between Age group, Specific switch costs, and Ratio, $F(1, 22) = 4.75$, $p < .04$, $\eta^2 = .18$. Separate analyses for the two age groups and the two ratio conditions showed significant specific switch costs for younger adults in the HI ratio condition, $F(1, 11) = 9.64$, $p < .01$, $\eta^2 = .47$, but not in the LI ratio condition, $p = .35$. The opposite pattern was obtained for older adults, who showed significant specific switch costs in the LI ratio condition, $F(1, 11) = 5.71$, $p < .04$, $\eta^2 = .33$ but not the HI ratio condition, $p = .93$ (see Fig. 1b).

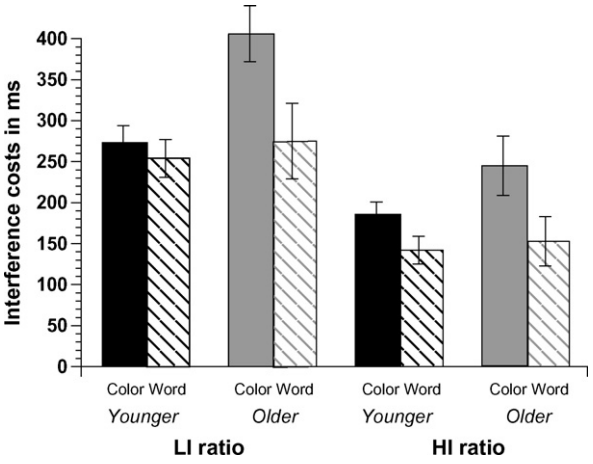

Fig. 2. Interference costs in milliseconds for the color and the word task in the low (LI) and the high (HI) ratio condition for younger and older adults.

Consistent with previous studies (Jacoby et al., 2003; Tzelgov et al., 1992), the interference effect was larger in the LI compared to the HI ratio condition, Compatibility × Ratio: $F(1, 22) = 169.48$, $p < .0001$, $\eta^2 = .89$ (see Fig. 2), and was found to be larger in the color than in the word task, Task × Compatibility: $F(1, 22) = 16.79$, $p < .0005$, $\eta^2 = .44$ (see Fig. 2).

As we expected age differences in interference effects to occur only under high conflict conditions, the four-way interaction between Age group, Ratio, Task, and Compatibility was of most interest. As this interaction was found to be significant, $F(1, 22) = 4.34$, $p < .05$, $\eta^2 = .18$, separate analyses were conducted for the LI and HI ratio conditions. Only for the LI, not for the HI ratio condition, we found a significant Age group × Task × Compatibility interaction, $F(1, 22) = 5.02$, $p < .04$, $\eta^2 = .20$. Separate ANOVAs for the two age groups and the two ratio conditions indicated a significant interaction between task and compatibility in the low ratio condition for older adults, $F(1, 11) = 12.40$, $p < .005$, $\eta^2 = .53$, but not for younger adults, $p = .33$. As can be seen in Fig. 2, interference

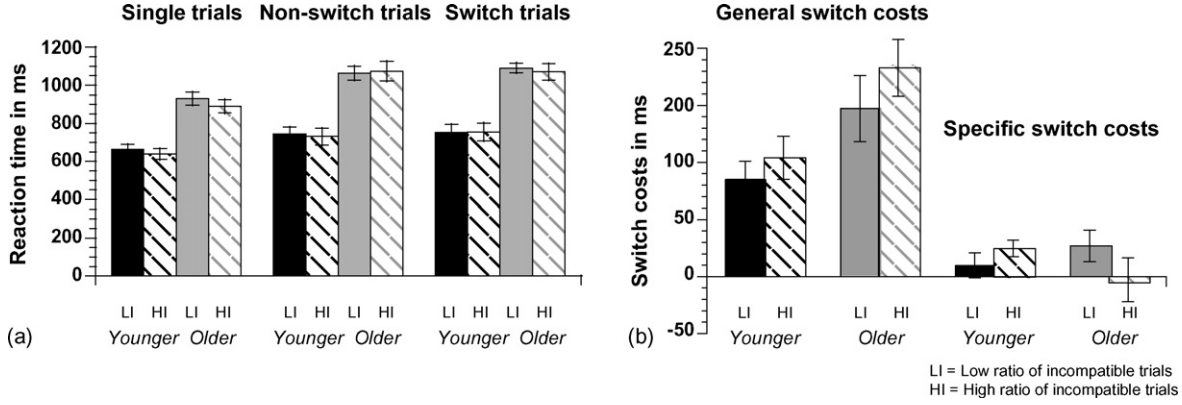

Fig. 1. (a and b) Reaction times in milliseconds for single, non-switch and switch trials in the low (LI) and the high (HI) ratio condition for younger and older adults (a). General switch costs (non-switch–single trials) and specific switch costs (switch–non-switch trials) in milliseconds in the low (LI) and the high (HI) ratio condition for younger and older adults (b).

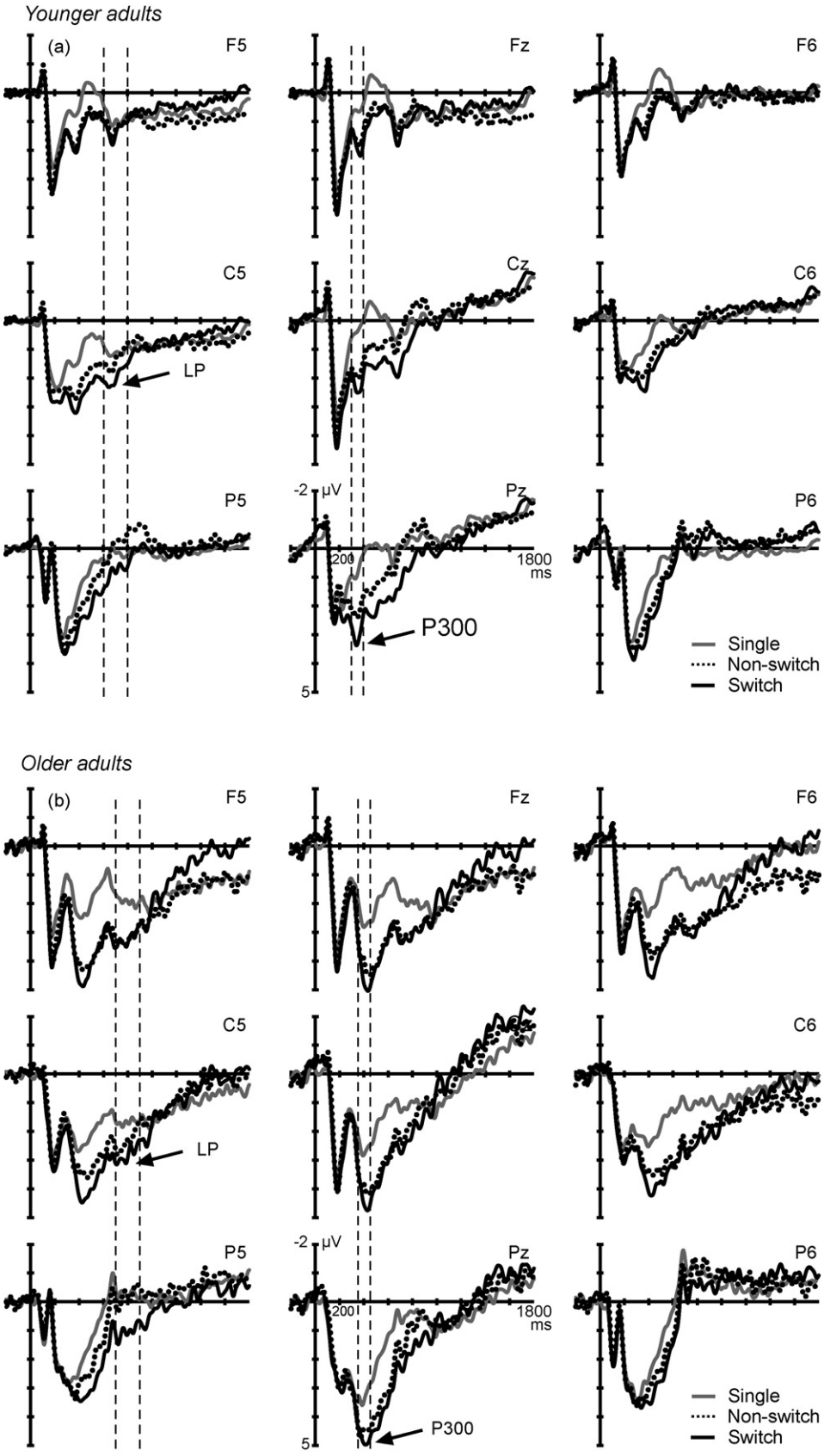

Fig. 3. (a and b) Grand average ERPs in the cue-target interval (CTI) for younger adults (a) and older adults (b) for single, non-switch and switch trials at the nine electrodes (F5, Fz, F6, C5, Cz, C6, P5, Pz, P6) that entered statistical analysis. The vertical bars indicate cue onset and tick spacing on the *x*-axis is 200 ms. Dashed vertical lines indicate the time windows that were used for statistical analysis.

effects were larger for older than younger adults in the color task in the low ratio condition.

3.1.2. Error rates

The same ANOVA design as for response times was performed for error rates. Participants showed higher error rates in non-switch trials compared to single trials, $F(1, 22) = 11.87$, $p < .002$, $\eta^2 = .35$, as well as in switch compared to non-switch trials, $F(1, 22) = 9.30$, $p < .006$, $\eta^2 = .30$. Moreover, more errors were committed on incompatible than on compatible trials, $F(1, 22) = 31.51$, $p < .0001$, $\eta^2 = .59$. Importantly, no age differences in error rates were obtained.

3.2. ERP data

3.2.1. Cue-target interval (CTI)

Fig. 3a and b displays the ERPs elicited by the task-set cues for single, non-switch, and switch trials for younger and older adults at the nine electrodes (F5, Fz, F6, C5, Cz, C6, P5, Pz, P6) that entered statistical analysis. The task-set cues for all trial types evoked a parietally distributed P300 component in younger and older adults. Following the P300, a second positive modulation for switch compared to non-switch trials can be observed at left and mid central recording sites for younger as well as for older adults. We will refer to this second positivity as late positivity (LP) in the following.

3.2.2. P300

As apparent from Fig. 3a and b, P300 latency at Pz was delayed for about 50 ms for older adults (396 ms) compared to younger adults (348 ms). Hence, we defined the mean P300 amplitude in different time windows for younger (300–400 ms) and older (350–450 ms) adults. The ANOVA for the P300 amplitudes involved the factors Age group (young, old), Trial type (single, non-switch, switch), Ratio (low, high), Task (color, word), and Electrode (F5, Fz, F6, C5, Cz, C6, P5, Pz, P6).

The analysis showed a main effect of Trial type, $F(2, 44) = 20.72$, $p < .0001$, $\eta^2 = .49$, an interaction of Trial type and Electrode, $F(16, 352) = 3.35$, $p < .008$, $\varepsilon = .30$, $\eta^2 = .13$, and a three-way interaction between Age group, Trial type, and Electrode, $F(16, 352) = 3.19$, $p < .01$, $\varepsilon = .29$, $\eta^2 = .13$. The latter interaction suggests a more flattened anterior to posterior distribution of the P300 in older compared to younger adults. Similar topographical differences as a function of age have been reported in several other studies (e.g., Friedman et al., 1997; Kray et al., 2005).

To further analyze the Trial type × Electrode interaction we performed post hoc analyses comparing either non-switch to switch trials or single to non-switch trials. The non-switch–switch comparison did neither reveal a significant main effect of trial type, nor a significant interaction involving the factor trial type (p's > .10). In contrast, the ANOVA for the single–non-switch comparison revealed a significant main effect of Trial type ($p < .0003$, $\eta^2 = .46$) as well as a significant Trial type × Electrode interaction ($p < .004$, $\eta^2 = .18$), reflecting the larger P300 in non-switch trials compared to single trials (see Fig. 3a and b).

Furthermore, we obtained a two-way interaction between Trial type and Ratio, $F(2, 44) = 9.42$, $p < .0005$, $\varepsilon = .94$, $\eta^2 = .30$, and a three-way interaction involving the factors Trial type, Ratio, and Electrode, $F(16, 352) = 2.22$, $p < .04$, $\varepsilon = .42$, $\eta^2 = .09$. Only for the single–non-switch comparison we found a significant interaction between Trial type and Ratio, $F(1, 22) = 22.03$, $p < .0001$, $\eta^2 = .50$, and between Trial type, Ratio, and Electrode, $F(8, 176) = 3.46$, $p < .01$, $\varepsilon = .52$, $\eta^2 = .14$. Separate analyses for the factor Trial type indicated a

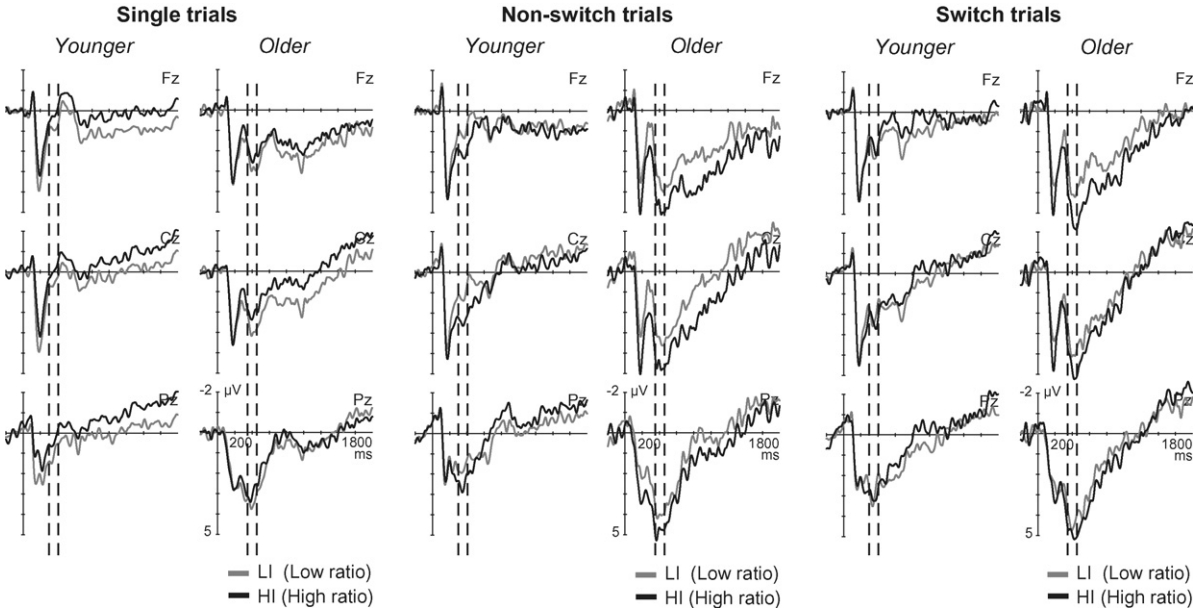

Fig. 4. Grand average ERPs in the cue-target interval (CTI) for younger and older adults for single, non-switch and switch trials in the low (LI) and the high (HI) ratio condition at three central electrodes (Fz, Cz, Pz). The vertical bars indicate cue onset and tick spacing on the x-axis is 200 ms. Dashed vertical lines indicate the time windows that were used for statistical analysis.

significant main effect of ratio for non-switch trials, $F(1, 22) = 5.81$, $p < .02$, $\eta^2 = .20$, and a marginally significant main effect of ratio for single trials, $F(1, 22) = 4.07$, $p < .06$, $\eta^2 = .16$, but no significant main effect of ratio was obtained for switch trials, $p = .42$. Post hoc tests for each electrode revealed significant interactions between the factors trial type and ratio at the electrodes Fz, F6, Cz, C5, C6, and Pz (p's $< .01$, η^2's $> .19$) (see Fig. 4).[2]

3.2.3. Late positivity (LP)

As can be seen in Fig. 3a and b, a late positive modulation (LP) being larger for switch than for non-switch trials followed the P300 at left central and parietal electrodes. We measured the late positivity (LP) within a 200 ms time window ranging from 600–800 ms in younger adults and 650–850 ms in older adults.[3] The ANOVA design was the same as for the P300.

The analysis revealed a main effect of Trial type, $F(2, 44) = 6.45$, $p < .004$, $\varepsilon = .95$, $\eta^2 = .23$, an interaction between Trial type and Electrode, $F(16, 352) = 4.57$, $p < .0001$, $\varepsilon = .43$, $\eta^2 = .17$, as well as an interaction between Trial type and Ratio, $F(2, 44) = 3.35$, $p < .05$, $\varepsilon = .85$, $\eta^2 = .13$. The post hoc contrasts for the factor trial type revealed a main effect of Trial type, $F(1, 22) = 4.25$, $p < .05$, $\eta^2 = .16$, an interaction between Trial type and Electrode, $F(8, 176) = 5.04$, $p < .0004$, $\eta^2 = .19$, and an interaction between Trial type and Ratio, $F(1, 22) = 6.88$, $p < .02$, $\eta^2 = .24$ for the single–non-switch comparison. Separate analyses for the factor ratio revealed a significant main effect of trial type only for the high ratio condition, $F(1, 22) = 6.90$, $p < .02$, $\eta^2 = .24$ but not for the low ratio condition ($p = .49$). Separate analyses for each of the electrodes revealed a main effect of trial type at the right frontal electrode F6: $F(1, 22) = 11.29$, $p < .003$, $\eta^2 = .34$ (see Fig. 3a and b).

Interestingly, in the non-switch–switch comparison we also found a significant interaction between Trial type and Electrode, $F(1, 176) = 6.67$, $p < .0002$, $\varepsilon = .43$, $\eta^2 = .23$. Separate ANOVAs for each of the electrodes showed a significant main effect of trial type at the electrode P5: $F(1, 22) = 12.11$, $p < .002$, $\eta^2 = .36$ (see Fig. 3a and b).

Taken together, the results of cue-related ERPs indicated that the two components were modulated by task switching. First, the P300 amplitudes were larger for switch and non-switch trials compared to single trials, and there was no significant difference in the P300 between switch and non-switch trials (see Fig. 3a and b).[4] Furthermore, the ratio manipulation affected the P300 under single-task and non-switching conditions but not under switching conditions (see Fig. 4). That is, in single trials the P300 was larger when the ratio of incompatible trials was low (LI ratio condition), whereas in non-switch trials the P300 was larger when the ratio of incompatible trials was high (HI ratio condition). Second, consistent with previous studies (Kieffaber and Hetrick, 2005; Miniussi et al., 2005; Moulden et al., 1998; Rushworth et al., 2002), a larger late positivity (LP) was obtained for switch than for non-switch trials at the left parietal electrode P5 (see Fig. 3a and b). However, the LP was also affected by general task-switching, being larger for non-switch and switch compared to single trials, an effect that was most pronounced at the right frontal electrode F6 (see Fig. 3a and b). Moreover, similar to the P300, the LP was modulated by the ratio of conflict trials, indicating that the effects of general task switching were larger for the high compared to the low ratio condition.

3.3. Target interval (TI), stimulus-locked ERPs

Fig. 5 shows the stimulus-locked ERPs for incompatible and compatible trials in the low (LI) and the high (HI) ratio condition for the two age groups. In the younger age group, a large negativity on incompatible trials emerged around 300 ms at left central and parietal electrodes and lasted until approximately 600 ms. In the older age group the negativity emerged later and was more pronounced at left parietal electrodes. Consistent with our prior report (Kray et al., 2005) this negativity will be termed Ni (negativity for incompatible trials) in the following. Although similar negativities to incompatible trials have also been reported in other studies (e.g., Liotti et al., 2000; West, 2004; West and Alain, 2000a,b), the peak latency of these components differed considerably across studies (around 380 ms (Kray et al., 2005) and 480 ms (West, 2004; West and Alain, 2000a)). In order to account for the latency effects and to examine conflict monitoring on an earlier and a later stage of processing, we analyzed the mean amplitude measures for the Ni in two consecutive time windows (300–470 and 470–640 ms), taking the additional factors Compatibility (compatible, incompatible) and Time window (early, late) into account.

Since this analysis revealed several significant two-, three-, and four-way interactions involving the factor time window, separate analyses for both time windows were performed.

In the *early time window* (300–470 ms) we found significant interactions between Age group and Compatibility, $F(1, 22) = 8.50$, $p < .008$, $\eta^2 = .29$, and Age group, Compatibility, and Electrode, $F(8, 176) = 5.00$, $p < .004$, $\varepsilon = .36$, $\eta^2 = .24$. Of

[2] In addition to these effects we obtained a significant three-way interaction between Age group, Task, and Electrode. Separate analyses for the two age groups revealed a significant effect of Task at the Electrode P6: $F(1, 11) = 5.64$, $p < .04$ for older adults, which reflects the larger right parietal P300 for the color (M: 3.28 μV; S.E.: 0.39), compared to the word task (M: 2.87 μV; S.E.: 0.40) for older adults.

[3] Note that right before the LP time window a negativity at frontal electrodes differentiated single from non-switch and switch trials. However, rather than reflecting an experimental effect, this difference seems to result from a component overlap with the P300. In fact, filtering out the P300 (and similar slow wave components) by applying a 1 Hz high pass filter reveals comparable negativities on single as well as non-switch and switch trials in younger and older adults.

[4] A reanalysis of the data from our previous study (Kray et al., 2005) also showed a larger P300 for non-switch compared to single trials however, no difference in the P300 was found for non-switch compared to switch trials. Since this study was performed in two sessions and yielded rather high trial numbers it does not seem reasonable to assume that the absence of an effect of specific task switching in the current study is due to low statistical power or sensitivity of the measurement.

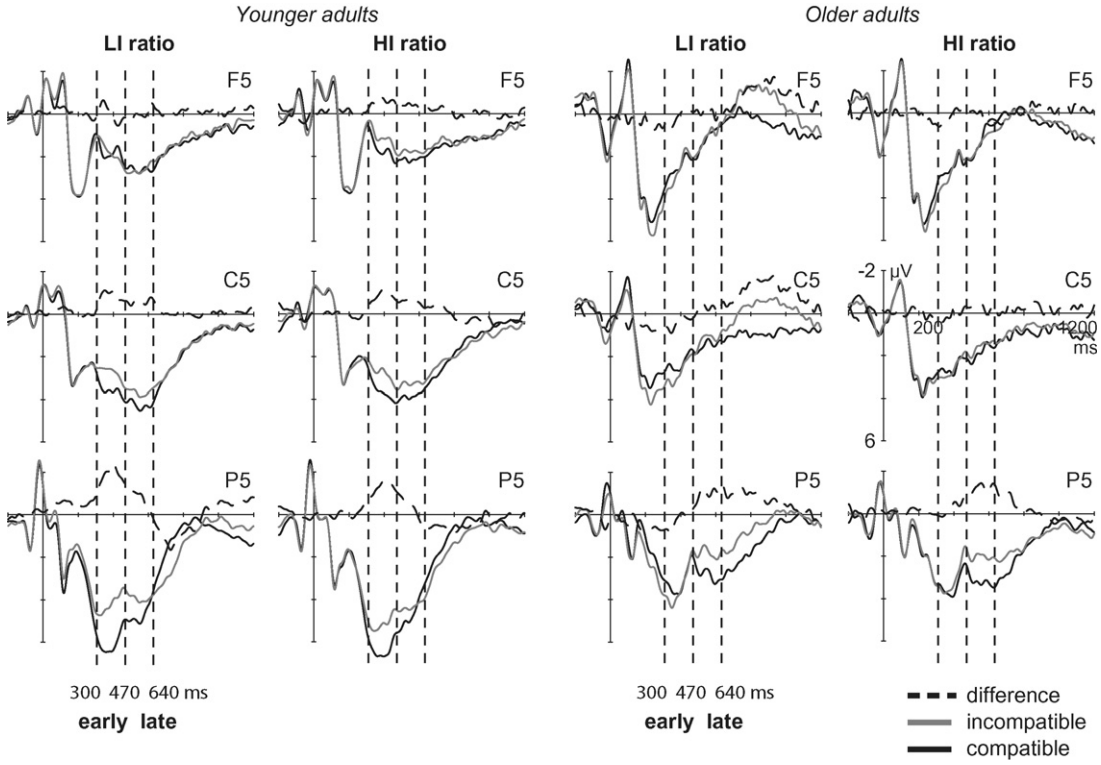

Fig. 5. Stimulus-related grand average ERPs in the target interval (TI) for compatible and incompatible trials and difference waves (incompatible–compatible) for younger and older adults in the low (LI) and the high (HI) ratio condition at three left lateral electrodes (F5, C5, P5). The vertical bars indicate target onset and tick spacing on the *x*-axis is 200 ms. Dashed vertical lines indicate the time windows that were used for statistical analysis.

most relevance in the present study were the significant interactions between Ratio, Compatibility, and Electrode, $F(1, 176) = 3.49$, $p < .01$, $\varepsilon = .50$, $\eta^2 = .14$, and between Age group, Ratio, Compatibility, and Electrode, $F(1, 176) = 8.51$, $p < .0001$, $\varepsilon = .50$, $\eta^2 = .28$. Separate ANOVAs for the two ratio conditions revealed significant interactions between Age group, Compatibility, and Electrode in the LI ratio condition, $F(8, 176) = 10.97$, $p < .0001$, $\varepsilon = .38$, $\eta^2 = .33$, but not in the HI ratio condition, $p = .29$. Furthermore, separate ANOVAs for compatible and incompatible trials revealed a significant interaction between Ratio, Electrode, and Age group for incompatible trials only, $F(8, 176) = 9.57$, $p < .008$, $\varepsilon = .45$, $\eta^2 = .30$. Separate analyses for both age groups and the two ratio conditions showed significant interactions between compatibility and electrode in the LI ratio condition for younger adults, $F(8, 88) = 10.32$, $p < .0003$, $\varepsilon = .29$, $\eta^2 = .48$, as well as for older adults, $F(8, 88) = 5.01$, $p < .009$, $\varepsilon = .33$, $\eta^2 = .31$. Post hoc comparisons for the two age groups, the two ratio conditions and each of the electrodes showed a significant main effect of compatibility in the LI ratio condition at the electrode P5 only for younger adults $F(1, 11) = 19.49$, $p < .001$, $\eta^2 = .64$ (see Fig. 5).

As we did not obtain any effects of general task switching on the Ni in our previous study (Kray et al., 2005) we focused the analysis on the effects of specific task switching. The non-switch–switch comparison in the early time window revealed a significant interaction between Trial type and Electrode, $F(8, 176) = 7.48$, $p < .0001$, $\varepsilon = .56$, $\eta^2 = .25$. Separate analysis for each of the Electrodes revealed main effects of Trial type at the electrodes P5 and Pz (p-values $< .01$, η^2's $> .24$), suggesting that the Ni was larger for switch compared to non-switch trials at these electrodes (see Fig. 6).

In the *late time window* (470–640 ms), we found significant interactions between Compatibility and Electrode, $F(8, 176) = 6.25$, $p < .001$, $\varepsilon = .34$, $\eta^2 = .22$, between Ratio, Compatibility, and Electrode, $F(8, 176) = 2.51$, $p < .05$, $\varepsilon = .45$, $\eta^2 = .10$, and between Age group, Ratio, Compatibility, and Electrode, $F(8, 176) = 3.30$, $p < .02$, $\varepsilon = .38$, $\eta^2 = .13$.

Separate analyses for the two ratio conditions revealed a significant interaction between Age group, Compatibility, and Electrode in the HI ratio condition, $F(8, 176) = 4.27$, $p < .01$, $\varepsilon = .32$, $\eta^2 = .16$, but not in the LI ratio condition, $p = .17$. Separate analyses for the two age groups and the two ratio conditions revealed significant two-way interactions between Compatibility and Electrode in the HI ratio condition for older adults, $F(8, 88) = 10.19$, $p < .0001$, $\varepsilon = .34$, $\eta^2 = .48$, but not for younger adults ($p = .19$). In order to further examine the topography of the compatibility effects for older adults in the HI ratio condition we performed post hoc tests for the ratio factor and each electrode. In the HI ratio condition significant main effects of Compatibility were found at the lateral parietal electrodes P5 and P6 (p-values $< .004$, η^2's $> .54$), indicating that the Ni was larger for incompatible compared to compatible trials (see Fig. 5).

Moreover, we obtained a significant three-way interaction between Task, Compatibility, and Electrode, $F(8, 176) = 2.88$, $p < .05$, $\varepsilon = .36$, $\eta^2 = .12$. Separate ANOVAs for each task revealed a significant Compatibility × Electrode interaction

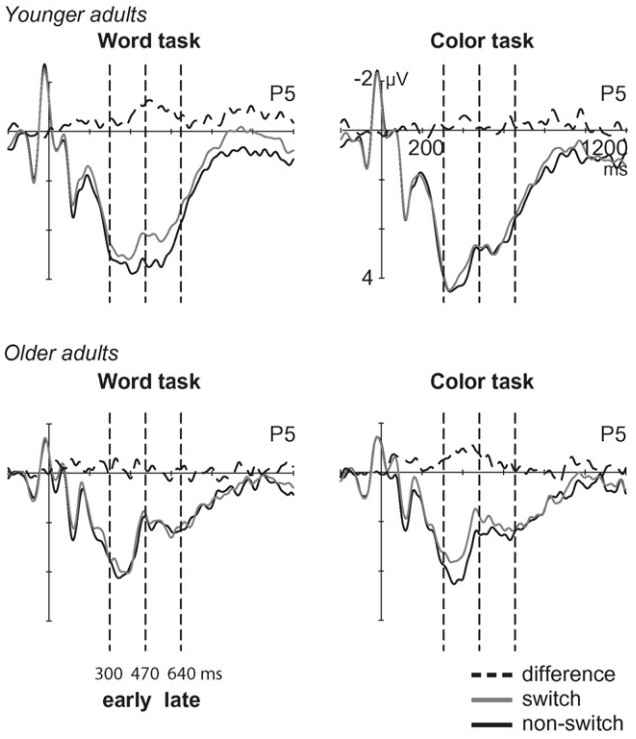

Fig. 6. Stimulus-related grand average ERPs in the target interval (TI) for non–switch and switch trials and difference waves (switch–non-switch) in the color and the word task for younger and older adults at the electrode P5.

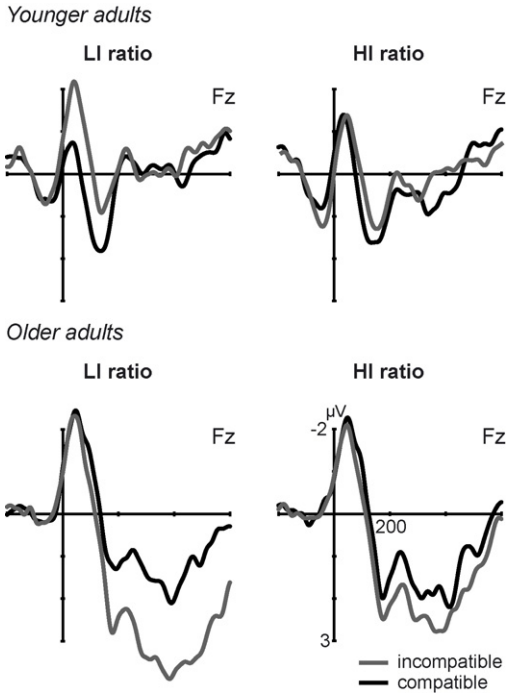

Fig. 7. Response-related grand average ERPs in the TI for compatible and incompatible trials in the low (LI) and the high (HI) ratio condition for younger and older adults at the electrode Fz. The vertical bars indicate response onset and tick spacing on the *x*-axis is 200 ms.

only for the color task, $F(8, 176) = 7.68$, $p < .002$, $\varepsilon = .37$, $\eta^2 = .26$, but was marginally significant for the word task ($p < .06$). Post hoc tests revealed significant main effects of Compatibility for the color task at the electrodes P5 and Pz (p-values $< .01$, η^2's $> .24$), reflecting the more negative waveforms for incompatible ($M = 4.1$ μV, S.D. = 3.3 μV, measured at Pz) than for compatible trials ($M = 5.1$ μV, S.D. = 3.5 μV, measured at Pz).

The non-switch–switch comparison for the late time window revealed significant interactions between Trial type and Electrode, $F(8, 176) = 5.29$, $p < .002$, $\varepsilon = .38$, $\eta^2 = .19$, and Age group, Trial type, and Task, $F(2, 44) = 7.22$, $p < .01$, $\eta^2 = .25$. Separate ANOVAs for each of the electrodes showed significant main effects of trial type at the electrodes P5 and Pz (p-values $< .01$, η^2's $> .26$), reflecting the more negative waveforms for switch compared to non-switch trials (see Fig. 6). To further analyze the Age group × Trial type × Task interaction we performed separate analysis for the two age groups. There was a significant Trial type × Task interaction for younger adults, $F(1, 11) = 6.76$, $p < .02$, $\eta^2 = .38$, but not for older adults ($p = .31$). Separate post hoc tests for each task showed a significant main effect of Trial type only in the word task for the younger age group, $F(1, 11) = 5.00$, $p < .05$, $\eta^2 = .31$ (see Fig. 6).

To sum up, the analyses of the stimulus-locked ERPs in the *early time window* revealed a larger negativity for incompatible trials (Ni) in the LI ratio condition compared to the HI ratio condition for younger but not for older adults at the left parietal electrode P5 (see Fig. 5). In the *late time window*, we found a significantly larger Ni for older adults in the high ratio (HI) condition, whereas younger adults did not show significant effects of compatibility in this time window. Moreover, we found more pronounced interference effects at left parietal electrodes in the color compared to the word task, which suggests task-specific interference effects in the Ni. However, the Ni was also influenced by task switching, being more negative for switch than for non-switch trials in both time windows. This effect was further modulated by Age group and Task in the late time window, suggesting that younger adults showed larger effects of task switching in the word compared to the color task (see Fig. 6).

3.4. Target interval (TI), response-locked ERPs

Fig. 7 shows the ERPs elicited by responses to compatible and incompatible Stroop trials, in the low and the high ratio condition for younger and older adults at electrode Fz. At around 40 ms, a correct response negativity (CRN) can be observed that was larger for incompatible than for compatible trials in the younger age group and of similar magnitude for both trial types in the older age group. CRN amplitude was defined as the mean amplitude from response onset until 100 ms thereafter. The CRN amplitude measures were examined using the same ANOVA design as for the target-locked analysis except for the factor electrode. As the CRN was maximal at the electrode Fz for both age groups, only Fz entered the analysis.

3.4.1. CRN amplitudes

The analysis of the CRN amplitude showed an interaction between Age group and Compatibility, $F(1, 22) = 6.23$,

$p < .02$, $\eta^2 = .22$ (see Fig. 7). Again, of most interest in this study was whether this effect was modulated by the ratio manipulation. Indeed, we obtained an interaction between Ratio and Compatibility, $F(1, 22) = 5.85$, $p < .02$, $\eta^2 = .21$ and a three-way interaction involving the factors Age group, Ratio, and Compatibility, $F(1, 22) = 5.94$, $p < .02$, $\eta^2 = .21$.

Separate ANOVAs for each age group revealed an interaction between Ratio and Compatibility for younger adults, $F(1, 11) = 7.75$, $p < .02$, $\eta^2 = .41$, but not for older adults ($p = .98$). Post hoc tests for the young age group indicated that the compatibility effect was reliable in the LI ratio condition, $F(1, 11) = 8.09$, $p < .02$, $\eta^2 = .42$, but not in the HI ratio condition ($p = .32$) (see Fig. 7). Furthermore, separate analyses for the factor Ratio were performed. A significant Age group × Compatibility interaction was obtained in the LI ratio condition, $F(1, 22) = 8.71$, $p < .007$, $\eta^2 = .28$, only. Post hoc tests for the factors Ratio and Compatibility revealed a significant effect of age only on compatible trials in the LI ratio condition, $F(1, 22) = 7.27$, $p < .01$, $\eta^2 = .25$, which reflects the smaller CRN on compatible trials for younger compared to older adults when the probability of compatible trials is high (see Fig. 7).

In sum, younger adults showed larger CRNs for incompatible compared to compatible trials in the LI, but not in the HI ratio condition. For older adults there were no reliable compatibility effects, neither in the LI nor in the HI ratio condition. Rather, older adults showed a CRN on compatible trials as well.

4. Discussion

The main goal of this study was to examine whether age differences in ERP components associated with the implementation of task-appropriate behavior and response monitoring are influenced by a task context with changing demands on conflict processing. Task context was manipulated by varying the ratio of incompatible to compatible Stroop trials. We expected that a task context in which incompatible trials are relatively rare would increase the demands on conflict processing since participants adjust their response strategy to compatible trials and are less engaged in the implementation of the appropriate task goals (Jacoby et al., 2003; Tzelgov et al., 1992). From this, it follows that on infrequent incompatible trials processing is less adapted to conflict and the demands on response monitoring are increased. Thus, the probability information can be used to build up expectancies about situations in which more or less attentional control is needed.

4.1. Behavioral data

The analysis of the behavioral data showed larger general switch costs when the task context mainly consisted of conflict trials (in the high ratio condition). At the first glance this result suggests increased demands on maintaining and coordinating task-sets when incompatible trials are relatively frequent. However, inspection of absolute response times instead of switch costs showed that smaller general switch costs in the LI ratio condition were due to increased latencies in single trials, whereas latencies were comparable in non-switch as well as switch trials (see Fig. 1a). This suggests that subjects only make use of the probability information in the less complex single-task condition in order to engage differently in the implementation of task goals under high and low conflict situations.

In contrast to previous studies we did not find age differences in general switch costs, presumably because all subjects were highly familiar and well practiced in the task(s). They already took part in a previous two-session study using a highly similar paradigm (Kray et al., 2005).[5] Moreover, age differences in general switch costs are usually smaller when there is no overlap at the level of response sets (that is, when each stimulus feature is mapped onto a different motor response), as in the present study (Mayr, 2001).

Younger adults showed significant specific switch costs in the high compared to the low ratio condition, suggesting that they are more impaired in switching between tasks, when they have to concurrently adapt to a context of frequent incompatible trials. At first sight it seems that older adults are more impaired in task-switching when the ratio of incompatible trials is low, as specific switch costs were larger in this condition. However, it is important to note that for older adults mean RTs in the high ratio condition, in contrast to the low ratio condition, were largest in both trial types (non-switch and switch trials), suggesting that older adults had problems to adapt to the task context not only in switch trials but also in non-switch trials.

Consistent with our predictions, we found larger interference effects when the ratio of conflict trials was low, which indicates that a decreased ratio of conflict trials leads to increased interference effects. This is in line with several studies that have shown that the Stroop interference effect is affected by the proportion of conflict trials (Jacoby et al., 2003; Tzelgov et al., 1992). Hence, subjects probably did not expect conflict when the ratio of incompatible trials was low and had to engage more in conflict monitoring when an infrequent incompatible trial occurred. Of most relevance for the present study was the fact that age differences in the Stroop interference effect were influenced by the ratio manipulation (see Fig. 2). Older adults showed larger interference effects than younger adults when the ratio of conflict trials was low. This effect was only found for the color, but not for the word task. Hence, there is evidence for age differences in the Stroop interference effect, but it is limited to situations of highest response conflict.

4.2. ERP data

4.2.1. Cue interval, P300

During task preparation we expected the P300 component to reflect adjustments to changes in the task context. The P300 has been assumed to reflect the encoding and updating of relevant

[5] In our previous two-session study (Kray et al, 2005) participants performed the same task, without the ratio manipulation. However, the two studies were at least 6 months apart from each other, suggesting that previous experience did not have a specific effect on the current results.

task context (Donchin and Coles, 1988), a function that is essential for the implementation of task-appropriate behavior. Replicating previous findings (Kray et al., 2005; West, 2004), P300 amplitude was larger for non-switch and switch trials compared to single trials. However, the P300 did not differentiate between non-switch and switch trials, suggesting a similar engagement in task-set updating in both trial types (see Fig. 3a and b). Consistent with several oddball studies (Friedman et al., 1997; Frodl et al., 2000) and our previous study (Kray et al., 2005) the P300 was more evenly distributed over the scalp in older adults, which supports interpretations that older adults might more strongly recruit frontal areas during context updating (Friedman et al., 1997).

One important new finding of this study was that P300 amplitude and reaction times varied as a function of trial type and ratio condition. P300 amplitudes elicited by the task-set cues were increased and reaction times were delayed under low compared to high ratio conditions in single trials, suggesting higher demands on task-set updating under single-task conditions when the ratio of conflict trials is low. In contrast, the P300 in non-switch trials was increased in the high ratio compared to the low ratio condition, which indicates that in non-switch trials more task-set updating is necessary to adapt to a high ratio of conflict trials (see Fig. 4). Hence, it appears that the engagement in task-set updating during the adaptation to task context strongly depends on whether participants have to switch or not. In single task conditions the cue itself is redundant since task switching is not necessary and participants may adapt to infrequent conflict trials by engagement in task-set updating. In contrast, under switching conditions participants are already engaged in task-set updating in order to implement the currently relevant task set. Here frequent conflict trials seem to call for stronger recruitment of updating processes as reflected in a larger P300. This finding suggests that the P300 as a measure for context updating reflects the flexible adjustment of processing resources during the implementation of task-appropriate behavior.

4.2.2. Cue interval, late positivity (LP)

In contrast to the P300 component that did not differentiate between switch and non-switch trials, we found a positive modulation for switches compared to non-switches at left parietal recording sites that we called late positivity (LP) (see Fig. 3a and b). Similar positivities have been reported in other studies (Miniussi et al., 2005; Moulden et al., 1998; Rushworth et al., 2002) and it has been suggested that this positive modulation might reflect the strategic anticipatory reconfiguration during switching (Kieffaber and Hetrick, 2005). The fact that the LP can also be observed in older adults is consistent with the lack of age differences in specific switch costs and supports the view that older adults are not impaired in task-switching per se (see e.g., Kray and Lindenberger, 2000). Moreover, the left parietal topography of the LP nicely fits to the results of recent fMRI studies showing that activity in the superior parietal cortex covaried with the magnitude of specific switch costs (Braver et al., 2003) and that posterior parietal regions are selectively activated by cues that require shifts of attention from one target dimension to another (Hopfinger et al., 2000; Werkle-Bergner et al., 2006). Even though cautiousness is required in making inferences from scalp-recorded ERPs on underlying brain structures these findings may suggest that the late positivity reflects increased activity of the parietal cortex during specific task switching.

Yet, we also found evidence for effects of general task switching on the LP component similar to those obtained for the P300. The LP was larger for switch and non-switch trials compared to single trials hence the effects of general task switching do not seem to be restricted to the P300 but also show up later during task-set preparation. Interestingly, these effects seem to be most pronounced at right frontal electrodes in older adults (see electrode F6 in Fig. 3b), which might point to a larger activation of right frontal areas during general task switching in older adults (see DiGirolamo et al., 2001).

4.2.3. Target interval, stimulus-related conflict processing

In the target-locked analysis we focused on the negativity to incompatible trials (Ni) (see Kray et al., 2005). The Ni appears to be comparable to the N450 that has first been reported by West and Alain (2000a). However, in contrast to the N450, the Ni peaked earlier (around 380 ms in our previous study (Kray et al., 2005)) and seemed to have a left fronto-central and parietal topography. By this it shows a higher resemblance to the negativity that has been shown by Liotti et al. (2000). Yet both components, the N450 as well as the Ni seem to peak later and show a more parietal distribution than the fronto-central N2 found in Go-Nogo- and Stop-Signal paradigms (see Falkenstein et al., 2002; Kok et al., 2004). Moreover, in contrast to the phasic N2 component, the Ni in the current study was more extended over time in younger as well as older adults. In order to more precisely investigate the processes reflected in the Ni component and to cover its extended time range we decided to examine the Ni in two consecutive time windows (300–470 and 470–640 ms).

In the *early time window* (300–470 ms) we found a larger Ni for conflict trials in the low ratio condition for younger adults at the left parietal electrode P5 (see Fig. 5), which is consistent with the results from West and Alain (2000b). However, no significant effect of compatibility was found for older adults in the early time window.

In contrast, in the *late time window* (470–640 ms) older, but not younger adults, showed a larger Ni on conflict trials in the high ratio condition at lateral parietal electrodes (see also Fig. 5). Taken together, these results suggest that younger as well older adults show stimulus-related conflict processing however, on different time scales, which is consistent with the Ni latency effects that we found in our previous study (Kray et al., 2005).

In younger adults the Ni was increased in the low ratio condition, which suggests that the component not only reflects stimulus-driven conflict processing but also the changes in the demands on conflict processing. In contrast, in older adults the Ni was increased in the high ratio condition. This finding supports the view that older adults perceive conflict even when

the ratio of incompatible to compatible trials is high and they should be able to adapt to the task context.

Nevertheless, it should be noted that given the temporal overlap between the Ni and the P300 component it is difficult to establish whether the effects in the Ni reflect an increased negativity or a reduced P300 component. However, the fact that the Ni does not seem to be affected by stimulus frequency (it is not larger for infrequent compared to frequent stimuli, see Fig. 5) favors the account that the Ni reflects stimulus-related conflict processing rather than context updating processes as reflected in the P300. This view is further supported by task-specific compatibility effects in the later time window. Here we found a larger Ni in the color than in the word task, which is in line with the larger interference effects in the color task in the behavioral data (see Brown and Besner, 2001; MacLeod and MacDonald, 2000).

In addition to the effects of conflict processing, we also obtained effects of task switching in both time windows. We found more negative waveforms for switch compared to non-switch trials in both time windows, a finding that has also been reported by others (Karayanidis et al., 2003; Kieffaber and Hetrick, 2005; Rushworth et al., 2002). From a functional point of view, this negativity has been suggested to either reflect control processes during stimulus-driven task-set reconfiguration or to be a consequence of the interference produced by the previous task-set (task-set inertia) (for a discussion, see Karayanidis et al., 2003; Rushworth et al., 2002). By showing that in younger adults in the late time window the switch effect was larger for the word compared to the color task, our results seem to be more consistent with the latter view. This finding suggests that conflict is increased, when participants have to switch from the more difficult color task-set to the easier word task set (see Fig. 6).

However, this finding also raises the question whether the effects in the Ni during conflict processing and the negativity for switch trials indeed reflect the modulation of the same component. The effects are largely overlapping in topography, being most pronounced at left parietal electrodes. Yet, as suggested by the difference waves illustrated in Figs. 5 and 6 the switch effects in younger adults seem to arise later (around 470 ms for the word task) than the compatibility effects (around 400 ms in the LI ratio condition). Given this it seems reasonable to assume that conflict that arises on the level of task-set switching is processed later in time than stimulus-driven conflict that is produced by incompatible Stroop trials. Nevertheless, given the complexity of the design of the current study and fact that the temporal characteristics of these different forms of conflict processing were not the main focus of the present study, it seems necessary to address this point more directly in future ERP studies.

4.2.4. Target interval, response-related conflict processing

First, it is important to note that the results on age differences in the CRN replicated and extend the results of our previous study (Kray et al., 2005) in which we also obtained a larger CRN on incompatible than on compatible trials for younger but not for older adults. The second important finding of the present study is that similar to the Ni, 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. 7). In addition, in the younger age group CRN amplitudes paralleled the interference costs obtained in response times, i.e., CRN effects and interference effects were enhanced when response conflict was increased.

On the one hand, this suggests that younger adults adjust their behavior depending on the task context, which means that in the low ratio condition they are less prepared for conflict on the infrequently appearing incompatible trials. On the other hand, if a conflict occurs the cognitive system is more sensitive to conflicting information and as a result the CRN is increased. Given these findings, we suggest that the CRN not only reflects response conflict, but also the subjects' ability to develop response strategies in adaptation to a given task context.

There is an ongoing debate about the functional significance of the CRN and it has been suggested that this component reflects either an artifact of stimulus-locked activity or occurs when the participant's representation of the correct and actual response is compromised (Coles et al., 2001). However, recent studies supported neither the first nor the second view (Bartholow et al., 2005; Vidal et al., 2003). Instead, Vidal et al. (2003) stated that it seems likely that CRN and ERN/Ne indeed reflect the same underlying processes. In contrast to the Vidal et al. (2000) study, in which participants performed a rather simple three choice reaction time task, results of this study showed significantly larger CRNs on incompatible than compatible Stroop trials for younger adults, supporting the view that the CRN reflects response-related conflict monitoring processes. This view seems to be further supported by recent studies of Allain et al. (2004) and Hajcak et al. (2005). They found a reduction in the CRN amplitude to precede error trials, suggesting that the CRN might reflect the implementation of response monitoring processes.

Moreover, our results are also consistent with findings from a study of Bartholow et al. (2005), who manipulated the ratio of compatible to 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.

Hence, our findings support the view that the CRN reflects response-related conflict monitoring processes and are consistent with the view that the ACC – as a putative generator of the CRN – evaluates and monitors conflict. The view that the ACC is involved in the generation of the CRN is further supported by an fMRI study (Carter et al., 2000), which also used the Stroop task and manipulated the probability of conflict trials. Results of that study demonstrated that the ACC showed significantly more response-related activity on incompatible trials when incompatible trials were rare, a finding that nicely supports the present ERP results.

In contrast to younger adults, older adults did not show reliable differences in the CRN between conditions, with enhanced amplitudes, independently of compatibility or ratio. The finding that the CRN did not differentiate between

compatible and incompatible trials in the older age group confirms findings of our previous study and suggests impairments of older adults in discriminating compatible from incompatible trials. Our data are also consistent with findings from Gehring and Knight (2000). They found that CRNs were enhanced for patients with frontal lobe lesions. Gehring and Knight (2000) 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. The ACC then signals conflict and this gives rise to enhanced CRN amplitudes on compatible trials also. Thus, older adults appear to differentiate less between compatible and incompatible trials. As a consequence they are not able to build up expectancies about the compatibility of the target stimulus, which might explain the absence of an effect of ratio in the older age group.

Taken together, our data support the view that the CRN reflects processing in a more general evaluative network that seems to be driven by the ACC and that comes into play when the outcome of a response is monitored. However, the CRN not only reflects response-related conflict processing, but also the degree to which conflict processing is adapted to a given task context. The purpose of such an evaluative function would be to provide signals for other brain areas, like the lateral PFC in order to achieve behavioral adaptation to conflict by strengthening task-relevant representations. On the basis of our findings we propose that older adults suffer from a compromised representation of the correct response, leading to conflict, even on compatible trials, which is reflected in increased CRN amplitudes. Due to this deficit in discriminating compatible from incompatible trials, older adults might be less able to build up expectancies about the compatibility of trials, and thus are impaired in the flexible adaptation to changes in the task context.

5. Conclusion

This study provides evidence for the view that age differences in behavioral and ERP correlates associated with the implementation of task-appropriate behavior and response monitoring are influenced by the task context. During the implementation of task-appropriate behavior the P300 component reflects the flexible adjustment of processing to the given task context (the ratio of conflict trials), whereas the effects of task switching are reflected in a later positive modulation for switch compared to non-switch trials. Age differences in the flexible adaptation to the task context can be observed during stimulus-driven conflict processing in the negativity for incompatible trials (Ni), but are most apparent during response monitoring. Whereas for younger adults the CRN reflects response-related conflict processing as well as the degree to which conflict processing is adapted to the task context, older adults seem to be impaired in discriminating compatible from incompatible trials and in the flexible adaptation to changes in the task context.

Acknowledgements

The Deutsche Forschungsgemeinschaft (grant SFB 378) supported this research. We thank the participants for their contribution to this study. We are grateful to Sandra Schappert and Jutta Eber for help during data acquisition and to Barbara Mock and Christian Doeller for valuable comments on earlier versions of this manuscript.

References

Allain, S., Carbonell, L., Falkenstein, M., Burle, B., Vidal, F., 2004. The modulation of the ne-like wave on correct responses foreshadows errors. Neuroscience Letters 372, 161–166.

Allport, D.A., Styles, E.A., Hsieh, S., 1994. Shifting intentional set: exploring the dynamic control of tasks. In: Umiltà, C., Moscovitch, M. (Eds.), Attention and Performance XV. The MIT Press, Cambridge, MA, US, pp. 421–452.

Band, G.P., Kok, A., 2000. Age effects on response monitoring in a mental rotation task. Biological Psychology 51, 201–221.

Bartholow, B.D., Pearson, M.A., Dickter, C.L., Sher, K.J., Fabiani, M., Gratton, G., 2005. Strategic control and medial frontal negativity: beyond errors and response conflict. Psychophysiology 42, 33–42.

Beringer, J., 2000. Experimental Run Time System. Berisoft Cooperation, Frankfurt.

Botvinick, M., Braver, T.S., Barch, D.M., Carter, C.S., Cohen, J.D., 2001. Conflict monitoring and cognitive control. Psychological Review 108, 624–652.

Braver, T.S., Reynolds, J.R., Donaldson, D.I., 2003. Neural mechanisms of transient and sustained cognitive control during task switching. Neuron 39, 713–726.

Brown, M., Besner, D., 2001. On a variant of Stroop's paradigm: which cognitions press our buttons? Memory and Cognition 29, 903–904.

Carter, C.S., Macdonald, A.W., Botvinick, M., Ross, L., Stenger, V.A., Noll, D., et al., 2000. Parsing executive processes: strategic vs. evaluative functions of the anterior cingulate cortex. Proceedings of the National Academy of Sciences, 97, 1944–1948.

Cohen, J., 1973. Eta-squared and partial eta-squared in fixed factor ANOVA designs. Educational and Psychological Measurement 33, 107–112.

Coles, M.G.H., Scheffers, M.K., Holroyd, C.B., 2001. Why is there an ERN/Ne on correct trials? Response representations, stimulus-related components, and the theory of error-processing. Biological Psychology 56, 173–189.

Davidson, D.J., Zacks, R.T., Carrick, C.W., 2003. Stroop interference, practice, and aging. Aging, Neuropsychology and Cognition 10, 85–98.

DiGirolamo, G.J., Kramer, A.F., Barad, V., Cepeda, N.J., Weissman, D.H., Milham, M.P., et al., 2001. General and task-specific frontal lobe recruitment in older adults during executive processes: an fMRI investigation of task-switching. Neuroreport 12 (9), 2065–2071.

Donchin, E., Coles, M.G., 1988. Is the P300 component a manifestation of context updating? Behavioral and Brain Sciences 11, 357–427.

Dulaney, C.L., Rogers, W.A., 1994. Mechanisms underlying reduction in Stroop interference with practice for young and old adults. Journal of Experimental Psychology: Learning, Memory and Cognition 20, 470–484.

Falkenstein, M., Hoormann, J., Hohnsbein, J., 2001. Changes of error-related ERPs with age. Experimental Brain Research 138, 258–262.

Falkenstein, M., Hoormann, J., Hohnsbein, J., 2002. Inhibition-related ERP components: variation with modality, age, and time-on-task. Journal of Psychophysiology 16, 167–175.

Friedman, D., Kazmerski, V., Fabiani, M., 1997. An overview of age-related changes in the scalp distribution of P3b. Electroencephalography and Clinical Neurophysiology 104, 498–523.

Frodl, T., Juckel, G., Gallinat, J., Bottlender, R., Riedel, M., Preuss, U., et al., 2000. Dipole localization of p300 and normal aging. Brain Topography 13, 3–9.

Gehring, J.W., Knight, R.T., 2000. Prefrontal cingulate interactions in action monitoring. Nature Neuroscience 3, 516–520.

Greenhouse, W.W., Geisser, S., 1959. On methods in the analysis of profile data. Psychometrika 24, 95–112.

Gratton, G., Coles, M.G., Donchin, E., 1983. A new method for off-line removal of ocular artifact. Electroencephalography and Clinical Neurophysiology 55, 468–484.

Hajcak, G., Nieuwenhuis, S., Ridderinkhof, K.R., Simons, R.F., 2005. Error-preceding brain activity: robustness, temporal dynamics, and boundary conditions. Biological Psychology (70), 67–78.

Holroyd, C.B., Coles, M.G.H., 2002. The neural basis of human error processing: reinforcement learning, dopamine, and the error-related negativity. Psychological Review 109, 679–709.

Hopfinger, J.B., Buonocore, M.H., Mangun, G.R., 2000. The neural mechanisms of top-down attentional control. Nature Neuroscience 3 (3), 284–291.

Jacoby, L.L., Lindsay, D.S., Hessels, S., 2003. Item-specific control of automatic processes: Stroop process dissociations. Psychonomic Bulletin and Review 10, 638–644.

Karayanidis, F., Coltheart, M., Michie, P.T., Murphy, K., 2003. Electrophysiological correlates of anticipatory and poststimulus components of task switching. Psychophysiology 40, 329–348.

Keppel, G., 1991. Design and Analysis: A Researcher's Handbook, 3rd edition. Prentice-Hall, Englewood Cliffs, New Jersey.

Kerns, J.G., Cohen, J.D., Mac Donald, A.W., Cho, R.Y., Stenger, V.A., Carter, C.S., 2004. Anterior cingulate conflict monitoring and adjustments in control. Science 303, 1023–1026.

Kieffaber, P.D., Hetrick, W.P., 2005. Event-related potential correlates of task switching and switch costs. Psychophysiology 42, 56–71.

Kliegl, R., Mayr, U., Krampe, R.T., 1994. Time-accuracy functions for determining process and person differences: an application to cognitive aging. Cognitive Psychology 26, 134–164.

Kok, A., Ramautar, J.R., De Ruiter, M.B., Band, G.P.H., Ridderinkhof, K.R., 2004. ERP components associated with successful and unsuccessful stopping in a stop-signal task. Psychophysiology 41, 9–20.

Kray, J., Eber, J., Lindenberger, U., 2004. Age differences in executive functioning across the life-span: the role of verbalization in task-preparation. Acta Psychologica 115, 143–165.

Kray, J., Eppinger, B., Mecklinger, A., 2005. Age differences in attentional control: an event-related potential approach. Psychophysiology 42, 407–416.

Kray, J., Lindenberger, U., 2000. Adult age differences in task-switching. Psychology and Aging 15, 126–147.

Kramer, A.F., Hahn, S., Gopher, D., 1999. Task coordination and aging: explorations of executive processing in the task switching paradigm. Acta Psychologica 101, 339–378.

Kramer, A.F., Kray, J., 2006. Aging and divided attention. In: Bialystok, E., Craik, F.I.M. (Eds.), Lifespan Cognition: Mechanisms of Change. Oxford University Press, New York, p. 397.

Lehrl, S., 1977. Mehrfachwahl-Wortschatz-Test B (MWT-B). [Multiple-Choice Knowledge Test-B (MWT-B)] Straube, Erlangen, Germany.

Liotti, M., Woldorff, M.G., Perez III, R., Mayberg, H.S., 2000. An ERP study of the temporal course of the Stroop color-word interference effect. Neuropsychologia 38, 701–711.

MacDonald III, A.W., Cohen, J.D., Stenger, V.A., Carter, C.S., 2000. Dissociating the role of the dorsolateral prefrontal and anterior cingulate cortex in cognitive control. Science 288, 1835–1838.

MacLeod, C.M., MacDonald, P.A., 2000. Interdimensional interference in the Stroop effect: uncovering the cognitive and neural anatomy of attention. Trends in Cognitive Sciences 4, 383–391.

Mayr, U., 2001. Age differences in the selection of mental sets: the role of inhibition, stimulus ambiguity, and response-set overlap. Psychology and Aging 16, 96–109.

McCarthy, G., Wood, C.C., 1985. Scalp distributions of event-related potentials: an ambiguity associated with analysis of variance models. Electroencephalography and clinical Neurophysiology 62, 203–208.

Miniussi, C., Marzi, C.A., Nobre, A.C., 2005. Modulation of brain activity by selective task sets observed using event-related potentials. Neuropsychologia 43, 1514–1528.

Monsell, S., 2003. Task switching. Trends in Cognitive Sciences 7, 134–140.

Moulden, D.J.A., Picton, T.W., Meiran, N., Stuss, D.T., Riera, J.J., Valdes-Sosa, P., 1998. Event-related potentials when switching attention between task-sets. Brain and Cognition 37, 186–190.

Nieuwenhuis, S., Ridderinkhof, K.R., Talsma, D., Coles, M.G.H., Holroyd, C.B., Kok, A., et al., 2002. A computational account of altered error processing in older age: dopamine and the error-related negativity. Cognitive, Affective and Behavioral Neuroscience 2, 19–36.

Ridderinkhof, K.R., Ullsperger, M., Crone, E.A., Nieuwenhuis, S., 2004. The role of the medial frontal cortex in cognitive control. Science 306, 443–447.

Rogers, R.D., Monsell, S., 1995. Costs of a predictable switch between simple cognitive tasks. Journal of Experimental Psychology: General 124, 207–231.

Rubin, O., Meiran, N., 2005. On the origins of the task mixing cost in the cuing task-switching paradigm. Journal of Experimental Psychology: Learning, Memory and Cognition 31, 1477–1491.

Rushworth, F.S., Passingham, R.E., Nobre, A.C., 2002. Components of switching intentional sets. Journal of Cognitive Neuroscience 14, 1139–1150.

Smith, E.E., Jonides, J., 1999. Storage and executive processes in the frontal lobes. Science 283, 1657–1661.

Stroop, J.R., 1935. Studies of interference in serial and verbal reactions. Journal of Experimental Psychology 18, 643–662.

Tzelgov, J., Henik, A., Berger, J., 1992. Controlling Stroop effects by manipulating expectations for color words. Memory and Cognition 20, 727–735.

Verhaeghen, P., De Meersman, L., 1998. Aging and the Stroop effect: a meta-analysis. Psychology and Aging 13, 120–126.

Vidal, F., Burle, B., Bonnet, M., Grapperon, J., Hasbroucq, T., 2003. Error negativity on correct trials: a reexamination of available data. Biological Psychology 64, 265–282.

Vidal, F., Hasbroucq, T., Grapperon, J., Bonnet, M., 2000. Is the 'error negativity' specific to errors? Biological Psychology 51, 109–128.

Wechsler, W., 1982. Handanweisung zum Hamburg-Wechsler-Intelligenztest für Erwachsene (HAWIE). [Manual for the Hamburg-Wechsler Intelligence Test for Adults]. Huber, Bern, Switzerland.

Werkle-Bergner, M., Benoit, R., Mecklinger, A., Kray, J., 2006. Switching between memory retrieval tasks: evidence from slow-wave recordings. In: Paper Presented at the Fourth International Conference on Memory, Sidney.

West, R., 2004. The effects of aging on controlled attention and conflict processing in the Stroop task. Journal of Cognitive Neuroscience 16, 103–113.

West, R., Alain, C., 2000a. Age related decline in inhibitory control contributes to the increased Stroop effect observed in older adults. Psychophysiology 37, 179–189.

West, R., Alain, C., 2000b. Effects of task context and fluctuations of attention on neural activity supporting performance of the Stroop task. Brain Research 873, 102–111.

Yeung, N., Botvinick, M.M., Cohen, J.D., 2004. The neural basis of error detection: conflict monitoring and the error-related negativity. Psychological Review 111, 931–959.