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Age differences in attentional control: An event-related potential approach

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Abstract

We examined age differences in event-related potentials (ERPs) associated with attentional control of task-set selection and response interference by means of a cue-based switching paradigm in which participants performed the color or word Stroop task. The results of ERPs in the cue interval indicated that P3 latencies were slowed for older adults, suggesting age-related slowing in updating currently relevant task sets. Older adults also showed a larger CNV under switching than nonswitching conditions, indicating age differences in maintaining task sets over longer periods of time. The results of target-locked ERPs revealed a negativity to incompatible Stroop trials (Ni) that was prolonged for older adults, suggesting age differences in early conflict processing. Response-locked ERPs showed a negative deflection to incompatible Stroop trials (CRN) only for younger adults, suggesting age differences also in response-related conflict processing.

Descriptors: Age differences, Attentional control, Task switching, Interference control, Event-related potential, Standard and reverse Stroop task

The main goal of this research is to examine age differences in attentional control when subjects have to adapt to continuous changes in the environment. How good are younger and older subjects in implementing task goals when they are required to switch between tasks? Are there age differences in resolving conflicts when irrelevant but task-associated information has to be ignored? Such cognitive processes have been associated with the ability of the cognitive system to control behavior. Generally, cognitive control is defined as higher-order cognitive activity that modulates lower-level processes, such as sensory and motor processes, in order to regulate and verify behavioral activity. It has been suggested that cognitive control is a multiple construct involving abilities such as focusing attention on relevant information, inhibiting irrelevant information, scheduling processes in complex tasks, planning a sequence of subtasks, and monitoring processes such as updating contents in working memory (e.g., Jonides & Smith, 1997; Miller & Cohen, 2001).

A paradigm that has been frequently used to examine the dynamics of control behavior is the task-switching paradigm. In this paradigm, participants switch between two tasks, for example, they either classify numbers as odd or even or letters as consonants or vowels (cf. Rogers & Monsell, 1995). Originally, task-switching costs were determined as the difference in performance between blocks of trials in which subjects perform only one task (here termed single-task blocks) or perform both tasks within the same block (here termed mixed-task blocks). These switching costs are henceforth termed general switch costs (cf. Kray & Lindenberger, 2000). The problem with the measurement of general switch costs is that between-block comparisons also include differences in working memory load, selection, and switching requirements or arousal. Therefore, Rogers and Monsell introduced the "alternating runs paradigm" in which participants switch between tasks on every second trial within the same block. Costs of switching between task sets were determined as the difference in performance between switch trials and nonswitch trials, termed specific switch costs (cf. Kray & Lindenberger, 2000). There is some evidence that age differences are much more pronounced in general switch costs than in specific switch costs, suggesting that older adults are not impaired in switching per se but in processes related to the switch situation such as the selection and maintenance of task sets (DiGirolamo et al., 2001; Kray, Eber, & Lindenberger, 2004; Kray & Lindenberger, 2000; Mayr, 2001; for a meta-analysis, see Verhaeghen & Cerella, 2002).

A number of factors influence the magnitude of task-switching costs. Rogers and Monsell (1995) showed that specific switch costs are substantially decreased when the time to prepare for the next task was increased. As most of the aging studies have shown that older and younger adults are able to reduce task-switching costs with increasing preparation time (Kramer, Hahn, & Gopher, 1999; Kray & Lindenberger, 2000; Meiran, Gotler, &

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Perlman, 2001), the ability to prepare for the next task seems to be relatively preserved in old age. A further factor that influences the magnitude of switch costs is task ambiguity that can be induced by overlap in stimulus and response features between the two task sets, like in the classical Stroop paradigm (Stroop, 1935). In the Stroop paradigm, the latency to name the color of a word is slower when the word spells an incompatible color name (e.g., RED written in blue ink) than a compatible color name (e.g., RED written in red ink), termed Stroop interference effect (Stroop, 1935).

The empirical evidence on age differences in the Stroop interference effect is rather mixed: In the context of task switching, older adults sometimes show a greater response interference effect; sometimes they do not (e.g., Kramer & Kray, in press). Similarly, a number of studies found greater Stroop interference effects for older than for younger adults (Dulaney & Rogers, 1994; Li & Bosman, 1996; Spieler, Balota, & Faust, 1996; West & Baylis, 1998), whereas a recent meta-analysis by Verhaeghen and De Meersman (1998) did not support the view of specific age-related differences in the Stroop interference effect. Instead, larger Stroop interference effects for older than for younger adults can also be explained by age differences in general slowing.

The Present Study

The general aim of this study is to identify age-related changes in event-related potentials (ERPs) during task switching. Specifically, we aim to examine ERP correlates of age differences in task-set selection during task preparation and in interference control during task execution. ERPs were recorded in a cue interval, in which the subjects prepare for the upcoming task, and in a target interval, in which responses to Stroop stimuli had to be given.

There are only a few studies that examined ERP components associated with task switching or age differences therein (Gehring, Bryck, Jonides, Albin, & Badre, 2003; Karayanidis, Coltheart, Michie, & Murphy, 2003; Moulden et al., 1998; West, 2004). Two of them are particularly important for the present study because task switching related ERPs were investigated by means of a cue-based version of the switching paradigm, as in our experiment. In a study by Moulden et al. two tasks were presented sequentially and randomly within a run. The cues elicited a larger occipital N200 component, a larger parietal P390, and a larger fronto-central N430 in switch trials than in nonswitch trials. The authors suggested that the N200 reflects switching-unspecific perceptual processing, whereas the two latter components reflect task-set and response-set shifting processes.

West (2004) examined age differences in ERP components associated with task switching. Similar to the present study, he combined a cue-based version of the task-switching paradigm with standard Stroop stimuli. In the cue interval, two late ERP components differed between mixed-task blocks and single-task blocks and also between younger and older adults. First, a parietally distributed P3 was more pronounced in mixed- than in single-task blocks. Age differences were only obtained for P3 latency and were interpreted in terms of age-related slowing in the updating of task-set representations in working memory. Second, a bipolar slow wave with an onset around 600 ms showed larger negative polarities at occipital–parietal electrodes and larger positive polarities at anterior frontal electrodes in the preparation interval for mixed- as compared with single-task blocks. The difference between mixed- and single-task blocks remained constant across the whole preparation interval in the younger group, but not in the older group, suggesting that older adults may have a deficit in maintaining task-relevant information over a longer period of time. In the target interval, West found a N450 component that was not affected by task-switching requirements in younger adults. In contrast, for older adults the N450 was reliable only in mixed-task blocks, when conflict was highest. In addition, a component called "conflict SP" was found to be more positive for incompatible than compatible trials and was also larger for younger adults in the color task (standard Stroop task) but not for the word task (reverse Stroop task). The N450 has been attributed to conflict detection, whereas the conflict SP has been associated with the resolution of conflicts. Notably, other studies also found a negativity to conflict stimuli, resembling the N450 (Liotti, Woldorff, Perez, & Mayberg, 2000; West & Alain, 2000).

Using event-related functional magnetic resonance imaging (fMRI), MacDonald, Cohen, Stenger, and Carter (2000) showed that different brain structures are involved in task selection and interference control. The authors also used a cue-based task-switching paradigm with Stroop stimuli and decomposed neural activity related to (a) the processing of the task-set cue information (i.e., task preparation) and (b) the processing of the target information (i.e., interference control). The left dorsolateral prefrontal cortex (DLPFC) was more activated when the cue indicated the less dominant color-naming task, whereas in the target interval the anterior cingulate cortex (ACC) was more activated for incompatible than compatible trials. The authors concluded that the DLPFC plays an important role for the representation and active maintenance of task demands (cf. Miller & Cohen, 2001), whereas the ACC is more involved in the monitoring and evaluation of conflicts (for similar views, see Gehring & Knight, 2000; MacLeod & MacDonald, 2000).

The specific aims of the present study are to examine whether age differences in the ability to adapt to only one task set or to switch between task sets in the cue interval are reflected in modulations of two ERP components, the P3 and CNV. To examine age differences at an early and late stage of conflict processing in the target interval, we investigated a negativity elicited by target stimuli (labeled Ni in the following) and a later negativity, the correct-response negativity (CRN; Coles, Scheffers, & Holroyd, 2001) elicited by the subject's response and visible in the response-locked ERPs.

For the cue interval, age differences in P3 latency would indicate that older adults are slower in updating the currently relevant task settings. For the CNV in the cue interval we expect amplitude differences between single- and mixed-task blocks for younger and older adults, as both age groups may differ in maintaining task-relevant information over a longer period of time. To the extent to which older adults have deficits at early and late stages of conflict processing, we expect age-related modulations in the Ni and the CRN in the target interval.

Method

Participants

Thirty-seven adults were recruited for a two-session study. Each session lasted about 3 h. All subjects received 45 Euro for participating. The younger participants were students at Saarland University and the older adults were recruited from a subject pool or by personal contact. Three younger and 6 older adults had to be excluded from data analyses because of EEG artifacts, eye-movement artifacts, or medication use.[1]

The effective sample consisted of 14 younger adults (mean age = 21.7 years, $SD = 2.15$, 6 female) and 14 older adults (mean age = 62.9 years, $SD = 1.9$, 6 female). To increase between-subjects effects, we recruited homogeneous samples of younger and older adults with a relatively small age range (cf. Picton et al., 2000). All participants reported having a right-hand preference and absence of color blindness.

Two psychometric tests were used as control variables to show the representative of the sample, 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). Consistent with other aging studies (cf. Verhaeghen & Salthouse, 1997), younger adults ($M = 59.64$, $SD = 6.92$) reached a substantially higher score than older adults ($M = 48.21$, $SD = 8.79$) on the Digit-Symbol Substitution test, $F(1,26) = 14.24$, $MSE = 1669.6$, $p < .01$, whereas we found no significant difference on the Spot-a-Word test score between younger ($M = 26.14$, $SD = 3.11$) and older adults ($M = 28.00$, $SD = 3.03$), $p > .12$.

Stimuli and Tasks

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

The participants were instructed to perform two tasks. In the word task, they had to respond to the meaning of the word with one of four response keys, and in the color task, they were asked to respond to the color. Each task was indicated by a task-set cue, that is, the letter string –Wor– was displayed for the word task and the letter string –Far– was used for the color task.[2] The same response keys were used for both tasks. 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).

Procedure

First, all participants filled out an informed consent and a short demographic questionnaire. Then, they performed the two psychometric tests and finally the experimental tasks. The experimental task began with an acquisition phase in order to familiarize the subjects with the response assignments of both tasks. All participants first performed two blocks of the color task in which only neutral stimuli were presented (i.e., colored letters "XXXX") and then two blocks of the word task in which the four words were presented uncolored. Each block consisted of 48 trials. The participants then worked through four practice blocks (two single- and two mixed-task blocks), in which all stimuli were ambiguous. The experimental phase consisted of 16 blocks, 8 single-task blocks and 8 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. Block order was constant across subjects and trial order was random within each block.

Each block consisted of 32 trials, yielding a total of 2 sessions $\times$ 16 blocks $\times$ 32 trials = 1024 trials. Single- and mixed-task blocks consisted of an equal number of response types (left index, left middle, right index, right middle) and compatibility types (compatible, incompatible). In addition, mixed-task blocks consisted of an equal number of color and word tasks.

Each trial began with a task-set cue (i.e., –Far– or –Wor–) (500 ms), followed by a blank screen (1800 ms). Immediately before the target presentation, a fixation cross was displayed (200 ms) in order to avoid strategy effects in the color task in which the participants can reduce the interference effects by putting their focus of attention away from the word. Hence, the time interval between the onset of the cue and target presentation was 2500 ms. The target (300 ms) was followed by a blank screen that remained visible until the response was made. The feedback "correct" or "wrong" was presented (500 ms) below the target to motivate subjects for a 3-h session. The time interval between feedback presentation and the next task-set cue was 1000 ms. After each experimental block, feedback about mean response times and percentage of errors was given. All participants were told to respond as quickly and accurately as possible.

Data Recording

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. The responses were registered with four external response buttons. The experiment was steered by the Software package Experimental Run Time System (ERTS, Beringer, 2000).

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 served as reference and the right mastoid was recorded as an active channel. The EEG and EOG signals were on-line bandpass filtered (DC: 70 Hz, 50-Hz notch filter) and digitized at 500 Hz. The vertical and horizontal EOG were recorded from two electrode pairs placed on the infra- and supra-orbital ridges of the right eye and on the outer canthi of the two eyes. Impedances were kept below 5 kΩ. To increase the signal-to-noise ratio, the EEG data were off-line lowpass filtered with 30 Hz prior to statistical analyses.[3]

Data Analysis

Behavioral data. The interpretation of age differences on the basis of difference scores is less informative because the obtained Age $\times$ Condition interactions can also be explained by age differences in the baseline performance (cf. Kliegl, Mayr, & Krampe, 1994). In this study, we use the natural logarithm of raw RTs, which is equivalent to ratio scores (cf. Kray & Lindenberger, 2000; Ratcliff, 1993). The purpose of this method is to express costs as proportions because ratio scores are generally less sensitive to baseline performance (Meiran, 1996). As the mean error rates were low and no age differences in error rates were obtained (younger adults: $M = 5.22$, $SD = 4.62$; older

[1]Some of the participants did not participate in the second session, 2 of them because of motivational reasons, 1 was red–green blind, 1 because of medication, and 5 because of eye-movement and data acquisition artifacts.

[2]The first three letters of the German word *Wort* indicated that the word task should be performed, and the first three letters of the German word *Farbe* indicated that the color task should be performed.

[3]For 2 of the subjects, due to strong drift artifacts, a bandpass filter (0.5–30 Hz) was applied.

Table 1. *Mean (SE) for Log-Transformed RTs and RTs as a Function of Age Group, Block Type, Compatibility Type, and Task Type*

			Log RT		RT	
Age group	Block type	Compatibility type	Color	Word	Color	Word
Younger	Single	Compatible	6.35 (0.03)	6.40 (0.03)	596 (21)	626 (24)
		Incompatible	6.57 (0.03)	6.59 (0.04)	756 (25)	765 (31)
		Interference	0.22 (0.02)	0.19 (0.02)	159 (12)	139 (15)
	Mixed	Compatible	6.42 (0.04)	6.49 (0.04)	645 (28)	684 (32)
		Incompatible	6.75 (0.03)	6.74 (0.04)	909 (34)	906 (37)
		Interference	0.33 (0.02)	0.27 (0.02)	263 (15)	222 (17)
Older	Single	Compatible	6.66 (0.04)	6.69 (0.04)	816 (36)	839 (32)
		Incompatible	6.94 (0.04)	6.82 (0.05)	1089 (47)	978 (49)
		Interference	0.28 (0.03)	0.14 (0.02)	273 (35)	138 (22)
	Mixed	Compatible	6.74 (0.05)	6.81 (0.05)	896 (49)	968 (53)
		Incompatible	7.08 (0.04)	7.04 (0.05)	1259 (52)	1231 (67)
		Interference	0.34 (0.04)	0.22 (0.02)	363 (39)	263 (28)

adults: $M = 3.79$, $SD = 2.13$), the analysis of the behavioral data will focus on response time measures. The analysis of variance (ANOVA) was based on log-transformed RTs of correct responses.

ERP-data analysis. ERP epochs were extracted off-line for two intervals: the cue interval and the target interval. ERPs in the cue interval were computed for each subject at all recording sites, with epochs extending from 200 ms before cue onset until 1800 ms thereafter. In the target interval ERPs were measured from 200 ms before target onset until 1200 ms and ERPs were measured from 200 ms before response onset until 600 ms. Only correct trials were averaged. Prior to averaging, trials containing eye-movement artifacts or other artifacts were excluded from further 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, Coles, and Donchin (1983).

We examined the P3 and the CNV in the cue interval and the Ni and the CRN in the target interval. Details for electrode selection and ANOVA designs are reported in the Results section. In case of significant interactions involving the electrode and age group factors, additional ANOVAs were conducted using amplitude-normalized data (McCarthy & Wood, 1985). Whenever necessary the Geisser–Greenhouse correction was conducted (Geisser & Greenhouse, 1958) and the original F value, the adjusted p values, and the epsilon values (ε) are reported. Scalp potential topographic maps of selected ERP results were generated using all electrode positions by means of a two-dimensional spherical spline interpolation (Perrin, Pernier, Bertrand, & Echallier, 1989) and a radial projection from Cz, which respects the length of the median arcs.

Results

Behavioral Data

An ANOVA was computed with the factors Age Group (younger, older), Trial Type (single, nonswitch, switch), Task Type (word, color), and Compatibility Type (compatible, incompatible). The factor Trial Type was defined as two orthogonal, within-subjects contrasts. In the first contrast, mean latencies of trials in single-task blocks were tested against mean latencies of trials in mixed-task blocks (general switch costs). In the second contrast, mean latencies of nonswitch trials were tested against mean latencies of switch trials (specific switch costs). The means of log-transformed RTs as well as RTs are displayed in Table 1 and the means of general and specific switch costs are shown in Table 2.

The ANOVA results revealed a reliable main effect of Age Group, $F(1,26) = 35.18$, $p < .01$, indicating that older adults responded much slower than younger adults. RTs were slower in mixed- than single-task blocks, that is, we found significant general switch costs, $F(1,26) = 109.37$, $p < .01$. Within mixed-task blocks, RTs were slower in switch trials than nonswitch trials, indicating reliable specific switch costs, $F(1,26) = 6.93$, $p = .01$. Moreover, responses were slower in incompatible than compatible trials, suggesting a significant Stroop interference effect, Compatibility Type: $F(1,26) = 438.30$, $p < .01$.

The magnitude of general switch costs interacted with task type and with age. General switch costs were greater in the word than color task, $F(1,26) = 6.65$, $p = .02$, being much greater for older than for younger adults, $F(1,26) = 7.76$, $p < .01$. Consistent with a variety of other studies, specific switch costs were rather small and age differences were absent (see Table 2).

The magnitude of the Stroop interference effect interacted with task type and with switching condition (see Table 1). The Stroop interference effect was greater in the color than word task,

Table 2. *Mean (SE) for General and Specific Switch Costs on the Basis of Log-Transformed RTs and RTs as a Function of Age Group and Task Type*

		Log RT		RT	
Age group	Task type	General switch costs	Specific switch costs	General switch costs	Specific switch costs
Younger	Color	0.12 (0.02)	0.02 (0.01)	96 (14)	17 (13)
	Word	0.11 (0.01)	0.00 (0.01)	94 (13)	1 (6)
Older	Color	0.10 (0.02)	0.01 (0.01)	116 (27)	10 (15)
	Word	0.17 (0.02)	0.02 (0.01)	185 (29)	29 (18)

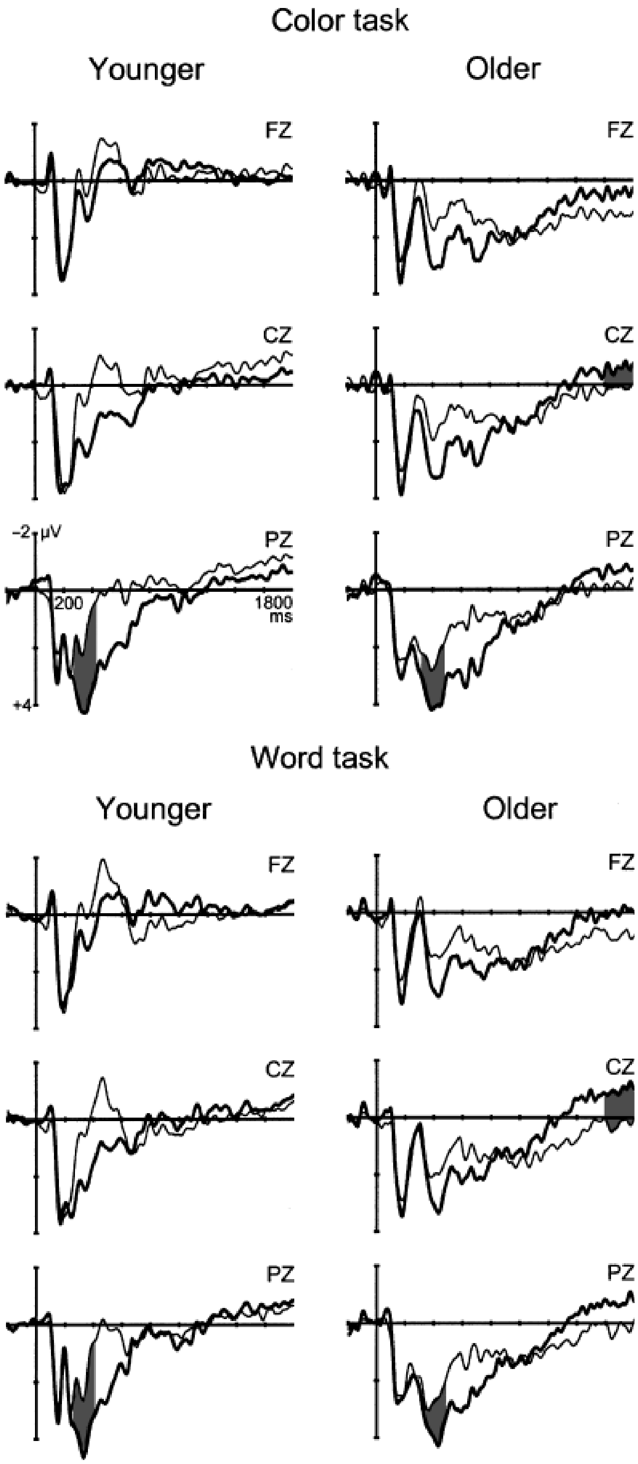

Figure 1. Grand average ERPs in the cue interval for *single-* (thin line) versus *mixed*-task (thick line) blocks separately for younger and older adults for the standard (color) and the reverse (word) Stroop task at three midline electrodes (FZ, CZ, PZ). The vertical bars indicate cue onset, tick spacing on the x-axis is 200 ms, and the shaded areas mark the time windows used for statistical analyses.

$F(1,26) = 19.16$, $p < .01$, and was also greater in mixed- than single-task blocks, $F(1,26) = 71.51$, $p < .01$. Importantly, the interaction between Age Group and the Stroop interference effect was not significant for the proportional scores, only for the difference scores, $F(1,26) = 6.00$, $p < .05$.

ERP Data

ERPs in the cue interval. Figure 1 displays ERP grand averages in the cue interval at three central electrodes elicited in single- and mixed-task blocks separately for younger and older adults and for the standard (color) and reverse (word) Stroop tasks. For all conditions a large positive component, the P3, was evoked at parietal electrodes for younger and older adults. Toward the end of the cue interval, a negative slow wave (CNV) emerged at central recording sites for the mixed- relative to single-task blocks in the older age group. The mean peak latencies of the P3 are shown in Table 3 and the mean of normalized P3 amplitudes are illustrated in Table 4.

The P3 component. The mean peak *latency* of the P3 was defined as the largest positive deflection between 300 and 600 ms poststimulus at the Pz electrode. Pz was used for latency analysis because the majority of subjects (85%) in both age groups showed largest P3 components at Pz. The ANOVA with the factors Age Group (young, old), Block Type (single, mixed), and Task Type (color, word) on P3 latency revealed a significant effect of Age Group, $F(1,26) = 23.47$, $p < .001$, indicating longer latencies for older than for younger adults, and a significant effect of Block type, $F(1,26) = 24.98$, $p < .001$, suggesting longer latencies for mixed- than for single-task blocks (see Table 3).

As the P3 differed in latency as a function of age group and experimental condition, P3 *amplitude* was defined as the mean amplitude in a 160-ms time interval centered around the mean P3 peak latency for each experimental condition and age group. The analysis included nine electrodes over frontal, central, and parietal areas (F5, Fz, F6, C5, Cz, C6, P5, Pz, P6). The ANOVA with the factors Age Group (young, old), Block Type (single, mixed), Task Type (color, word), and Electrode showed a significant main effect of Block Type, $F(1,26) = 34.40$, $p < .001$, and of Electrode, $F(8,208) = 14.06$, $p < .001$. Moreover, the interaction between Age Group, Block Type, Task Type, and Electrode was significant, $F(8,208) = 3.45$, $p < .05$, $\varepsilon = .39$. Importantly, this interaction remained significant after amplitude normalization (McCarthy & Wood, 1985), $F(8,208) = 4.05$, $p < .01$, $\varepsilon = .38$. To further explore this latter interaction, separate analyses were conducted for each Block Type and Task Type for amplitude-normalized data (see Table 4). In mixed-task blocks the interaction between Age Group and Electrode was significant for the

Table 3. *Mean (SE) for the P3 Peak Latency at Pz as a Function of Age Group, Block Type, and Task Type*

Age group	Block type	Task type	P3
Younger	Single	Color	328 (3.98)
		Word	336 (5.90)
	Mixed	Color	349 (5.49)
		Word	335 (4.69)
Older	Single	Color	389 (10.97)
		Word	395 (13.97)
	Mixed	Color	409 (14.44)
		Word	412 (13.74)

Note: The ranges of P3 latencies varied between 302 and 396 ms across conditions for younger adults and between 310 and 496 ms for older adults.

Table 4. *Mean (SE) for the P3 Normalized Amplitudes as a Function of Age Group, Block Type, and Task Type*

		Color		Word	
Age group	Electrode	Single	Mixed	Single	Mixed
Younger	F5	0.007 (0.010)	0.009 (0.006)	0.003 (0.010)	0.010 (0.006)
	Fz	0.008 (0.012)	0.009 (0.006)	– 0.001 (0.011)	0.010 (0.007)
	F6	0.006 (0.012)	0.006 (0.007)	– 0.004 (0.011)	0.009 (0.006)
	C5	0.021 (0.009)	0.022 (0.007)	0.021 (0.009)	0.022 (0.007)
	Cz	0.015 (0.010)	0.021 (0.007)	0.007 (0.012)	0.021 (0.008)
	C6	0.022 (0.010)	0.018 (0.006)	0.017 (0.010)	0.020 (0.006)
	P5	0.035 (0.007)	0.032 (0.007)	0.043 (0.008)	0.032 (0.007)
	Pz	0.032 (0.009)	0.038 (0.008)	0.030 (0.012)	0.036 (0.008)
	P6	0.040 (0.007)	0.035 (0.007)	0.040 (0.008)	0.034 (0.006)
Older	F5	0.012 (0.007)	0.020 (0.006)	0.014 (0.008)	0.019 (0.007)
	Fz	0.016 (0.009)	0.022 (0.007)	0.016 (0.009)	0.021 (0.007)
	F6	0.019 (0.008)	0.023 (0.006)	0.014 (0.009)	0.021 (0.006)
	C5	0.017 (0.007)	0.020 (0.005)	0.020 (0.007)	0.021 (0.005)
	Cz	0.019 (0.011)	0.024 (0.008)	0.024 (0.010)	0.024 (0.007)
	C6	0.022 (0.008)	0.024 (0.007)	0.020 (0.010)	0.021 (0.006)
	P5	0.028 (0.005)	0.022 (0.004)	0.032 (0.005)	0.025 (0.003)
	Pz	0.035 (0.010)	0.032 (0.007)	0.036 (0.010)	0.033 (0.007)
	P6	0.035 (0.006)	0.026 (0.005)	0.028 (0.006)	0.027 (0.004)

color task as well as for the word task, $F(8,208) = 5.05$, $p < .01$, $\varepsilon = .33$; $F(8,208) = 3.20$, $p < .05$, $\varepsilon = .40$, respectively, suggesting that the P3 amplitude increased from frontal over central to parietal recording sites to a larger extent in younger compared to older adults. In single-task blocks, the interaction between Age Group and Electrode was only significant for the word task, $F(8,208) = 3.81$, $p < .01$, $\varepsilon = .43$, but not for the color task, $F(8,208) = 1.00$, $p < .39$, $\varepsilon = .35$.

The CNV. As visual inspection of the grand average ERP waveforms suggested that the CNV differences between single- and mixed-task blocks emerged at around 1300 ms and extended until 1800 ms, we performed separate ANOVAs for the two time windows in which the CNV effects were largest (1400–1600 ms and 1600–1800 ms). For the first time window we only found a main effect of Electrode, and therefore, we focused the further analyses on the second time interval.

The ANOVA with the factors Age Group (young, old), Task Type (color, word), and Electrode (F5, Fz, F6, C5, Cz, C6, P5, Pz, P6) revealed a significant main effect for Electrode, $F(8,208) = 4.07$, $p < .01$, $\varepsilon = .55$, and a significant interaction between Task Type and Electrode, $F(8,208) = 3.30$, $p < .01$, $\varepsilon = .59$. Furthermore, the three-way interaction between Block Type, Task Type, and Electrode was significant, $F(8,208) = 2.41$, $p < .05$. To understand the nature of this interaction, separate ANOVAs were conducted for each task type. For the word task an interaction between Block Type and Electrode was found, $F(8,208) = 2.62$, $p < .04$, $\varepsilon = .49$, but not for the color task, $F(8,208) = 0.43$, $p < .75$, $\varepsilon = .42$, indicating that the distribution of the CNV was different under single- and mixed-task conditions only for the word task.

Most importantly, we obtained a significant interaction between Age Group and Block Type $F(1,26) = 4.23$, $p < .05$, $\varepsilon = .58$, indicating that the CNV in single- and mixed-task blocks was different for younger and older adults. Separate ANOVAs for the two age groups showed that the CNV was larger in mixed than in single blocks in the older age group, $F(1,13) = 4.81$, $p < .05$, but not in the younger age group, $F(1,13) = 0.39$, $p < .54$ (see Figure 1).

ERPs in the target interval. Figure 2 shows the grand average ERP waveforms at FCz and topographic maps for the amplitude difference between incompatible and compatible Stroop stimuli in the time windows that were used for statistical analysis of the Ni component.

The mean peak *latency* of the Ni was measured as maximum amplitude difference between incompatible and compatible conditions between 200 and 500 ms poststimulus at Cz. The ANOVA with the factors Age Group (young, old), Block Type (single, mixed), and Task Type (color, word) revealed a significant effect of Age Group, $F(1,26) = 8.74$, $p < .01$, and Task Type, $F(1,26) = 10.75$, $p < .01$. In addition, there was a three-way interaction between Age Group, Block Type, and Task Type: $F(1,26) = 5.74$, $p < .05$ (see Table 5). Therefore, tests were performed separately for each age group.

For the younger age group we obtained a main effect of Block Type, $F(1,13) = 5.99$, $p < .05$, suggesting that younger adults showed longer Ni latencies in mixed- than in single-task blocks (see Table 5). In contrast, for the older age group there was an interaction between Block Type and Task Type, $F(1,13) = 9.29$, $p < .01$, indicating that Ni latencies were longer in mixed- than in single-task blocks for the color task but not for the word task.

As the Ni differed in latency as a function of age groups and experimental conditions, the Ni *amplitude* was defined as the mean amplitude in a 100-ms time interval centered around the mean Ni peak latency in each experimental condition and age group. In line with a prior study (Liotti et al., 2000) the Ni showed a frontocentral distribution. Therefore, we selected nine medial frontal and central electrodes (F3, Fz, F4, FC3, FCz, FC4, C3, Cz, C4) for the statistical analyses. The ANOVA included the factors Age Group (young, old), Block Type (single, mixed), Task Type (color, word), Compatibility Type (compatible, incompatible), and Electrode.

For Ni amplitude significant main effects of Electrode, $F(8,208) = 13.55$, $p < .001$, $\varepsilon = .41$, and of Compatibility Type, $F(1,26) = 15.53$, $p < .001$, were obtained, indicating that Ni amplitude was more negative for incompatible than compatible trials. Furthermore, we found an interaction between Compatibility Type, Task Type, and Electrode, $F(8,208) = 2.86$, $p < .05$,

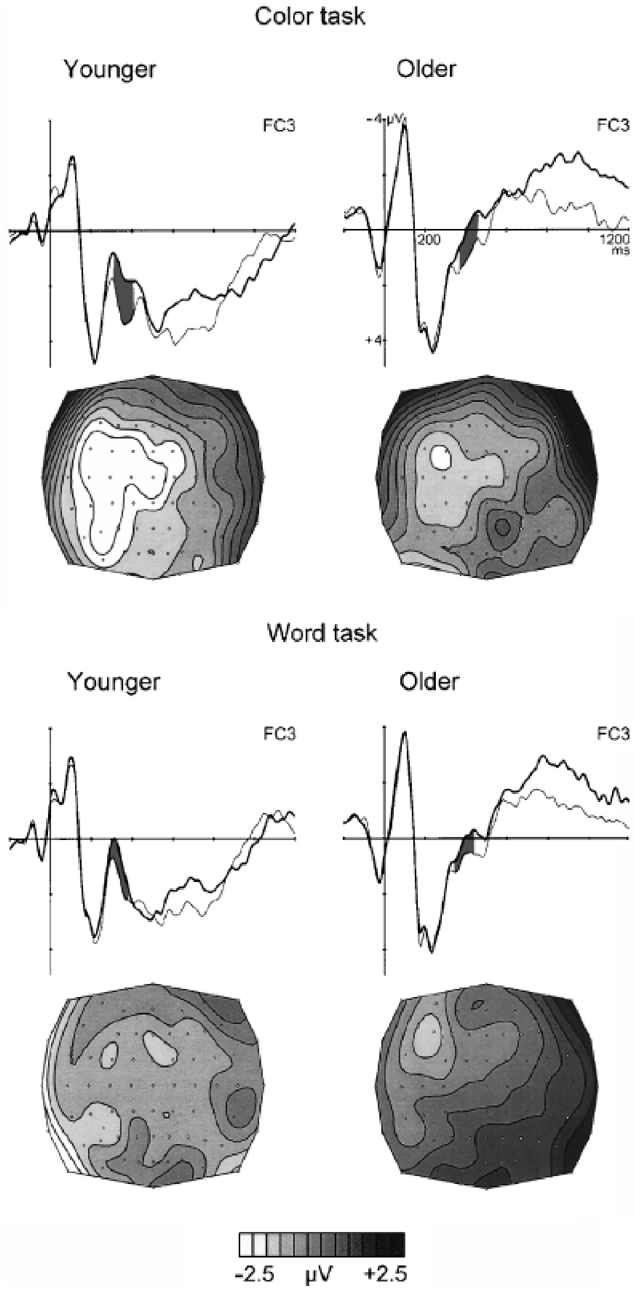

Figure 2. Grand-average ERPs in the target interval for *compatible* (thin line) and *incompatible* (thick line) Stroop stimuli, separately for the standard (color) and the reverse (word) Stroop tasks for younger and older adults for single-task blocks. The vertical bars indicate target onset, tick spacing on the x-axis is 200 ms, and the shaded areas mark the time windows used for statistical analyses. The corresponding topographical maps show the distribution of the amplitude differences between incompatible and compatible Stroop trials in the time windows that were used for statistical analysis.

$\varepsilon = .41$, suggesting that the topographic distribution of the interference effect was different in the two tasks. In fact, the three-way interaction remained significant after amplitude normalization, $F(8,208) = 3.02$, $p < .05$, $\varepsilon = .44$. As no interaction involving Age Group, Compatibility Type, and Electrode was obtained, it can be concluded that neither the magnitude nor the topography of the Ni was affected by age.

Table 5. *Mean (SE) for the ERPs in the Target Interval (Ni, CRN) as a Function of Age Group, Block Type, and Task Type*

Age group	Block type	Task type	Ni	CRN
Younger	Single	Color	358 (10.99)	86 (7.28)
		Word	331 (11.62)	75 (8.77)
	Mixed	Color	383 (10.73)	83 (8.16)
		Word	368 (16.37)	82 (10.60)
Older	Single	Color	401 (14.28)	83 (10.00)
		Word	389 (11.85)	80 (12.21)
	Mixed	Color	425 (11.65)	82 (6.34)
		Word	371 (14.56)	76 (9.57)

Note: The mean peak latency of the Ni and CRN was measured as maximum amplitude difference between incompatible and compatible Stroop trials at Cz and FCz, respectively.

Figure 3 displays the grand average ERP waveforms for responses to incompatible and compatible stimuli at FCz separately for younger and older adults and the corresponding topographical maps for the amplitude difference between incompatible and compatible Stroop trials. As apparent from the figure, in younger adults, correct responses to incompatible stimuli were immediately followed by a negativity, the so-called "Correct response negativity" (CRN).

The CRN was defined as the mean amplitude difference between incompatible and compatible conditions between 30 and 130 ms after the subjects' response at the FCz electrode. The

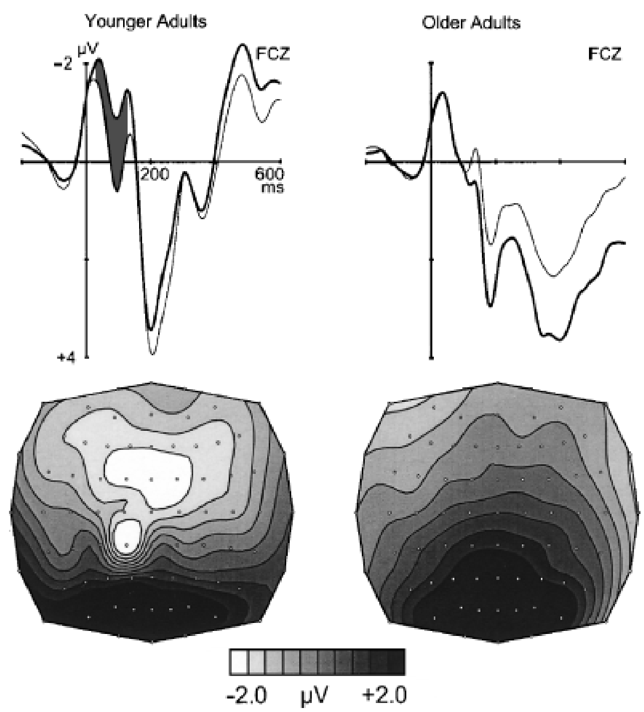

Figure 3. Response-locked grand-average ERPs (at the top) for *compatible* (thin line) and *incompatible* (thick line) Stroop stimuli at FCz for younger adults and older adults aggregated across experimental conditions. The vertical bars indicate response onset, tick spacing on the x-axis is 200 ms, and the shaded areas mark the time windows used for statistical analyses. The corresponding topographical maps show the distribution of the amplitude differences between incompatible and compatible Stroop trials in the time window that was used for statistical analysis.

ANOVA with the factors Age Group (young, old), Block Type (single, mixed), and Task Type (color, word) for the mean peak *latency* of this component did not reveal a significant effect of age or other significant effects, suggesting that the CRN peak latency was similar in both age groups and across experimental conditions (see Table 5).

The analysis of CRN *amplitude* included the factors Age Group (young, old), Block Type (single, mixed), Task Type (color, word), Compatibility Type (compatible, incompatible), and Electrode (F3, Fz, F4, FC3, FCz, FC4, C3, Cz, C4). The results showed a significant effect of Compatibility Type, $F(1,26) = 4.30$, $p < .05$, indicating that the CRN was more negative for incompatible than compatible trials. Moreover, an interaction between Age Group and Compatibility Type was obtained, $F(1,26) = 5.83$, $p < .05$. The CRN effect was highly significant in the younger age group, $F(1,13) = 11.53$, $p < .01$, and absent in the older age group, $F(1,13) = 0.05$, $p < .82$ (see Figure 3).

Discussion

The focus of this study was on the search for behavioral and ERP correlates of age differences in task-switching behavior. We used a cue-based switching paradigm with Stroop stimuli that allows us to separately examine ERP components in the cue and the target intervals. Consistent with previous findings (e.g., Kray & Lindenberger, 2000; Verhaeghen & Cerella, 2002), we found an age-related increase in general switch costs and no age differences in specific switch costs. Generally, the phenomenon of age differences in general switch costs is relatively independent of task-specific processes because it has been found in a variety of different task domains and studies (cf. Kramer & Kray, in press). In the present study, however, age differences in general switch costs were greater for the word task than the color task. There is some evidence that the magnitude of switch costs depends on the dominance of one task set relative to the other task set. For instance, Allport, Styles, and Hsieh (1994), using Stroop stimuli in a task-switching paradigm, found that switching to the more strongly learned task (here the word-naming task) results in greater switching costs. Consistent with this view, in the present study, general switch costs were larger for the word than the color task. Older adults were faster in the more familiar word tasks than in the color task.[4] Thus, it is reasonable to assume that the asymmetry of general switch costs between the color and word tasks for older adults is related to the asymmetry between both task sets. Hence, it seems that older adults have more problems disengaging from the more unfamiliar color task than younger adults do.

Results of a recent meta-analysis suggest that age differences in the Stroop interference effect can be explained by age differences in general slowing (Verhaeghen & De Meersman, 1998). Similarly, in the present study age differences in the Stroop effect were only reliable when age differences in general speed of responding are not taken into account (on the basis of difference scores). When age differences in general speed were controlled, age differences in Stroop interference disappeared. In line with a few studies that investigated the reverse Stroop effect, we found a slowing of responding to the word task when the color was incompatible with the word meaning in both age groups. This reverse Stroop effects was smaller than the standard Stroop effect (e.g., Atkinson, Drysdale, & Fulham, 2002; Ruff, Woodward, Laurens, & Liddle, 2001; West, 2004). This asymmetry in the magnitude of the Stroop interference effects has been explained by the difference in practice between both tasks, because word reading is the more strongly trained task (Cohen, Dunbar, & McClelland, 1990). Consistent with prior studies (West, 2004), Stroop interference increases when subjects are required to switch between both tasks compared to when subjects are required to perform only one task in a block. This suggests that response interference is greater when both task sets are currently relevant and have to be maintained in an active state.

Taken together, the behavioral data suggest that older adults have problems at a general level of switching between task sets, in particular, in switching to the more familiar (word naming) task. No age differences were obtained in specific switch costs, that is, the reconfiguration of task sets on a trial-to-trial basis and in Stroop interference, that is, suppression of task-irrelevant information.

ERP Correlates of Task-Set Selection

Consistent with previous studies a parietally distributed P3 was evoked by task cues that was larger under switching conditions (i.e., in mixed-task blocks) than nonswitching conditions (West, 2004). Generally, the P3 is assumed to reflect processes that encode and update the currently relevant task context (e.g., Donchin & Coles, 1988; Mecklinger & Ullsperger, 1993). In the present study, the P3 presumably reflects the updating of task sets for the word or color task. Our results indicate that the P3 latency is significantly slowed in the older group and under switching conditions. Age-related slowing of P3 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 Polich, 1996).

In contrast to the age effects for P3 peak latency, no age effects for P3 amplitude were found, suggesting that both age groups are equally efficient in updating the currently relevant task sets. Most obvious was that the P3 amplitude was substantially larger for switching conditions in both tasks. It is also noteworthy that the topography of the P3 was significantly modulated by age only in the word task. In the word task, in which general switch costs were also higher for older adults, the P3 topography took the form of a more flattened anterior–posterior distribution, specifically a loss of the centro-parietal focus in the older adults. Age-related changes in the topography of the P3 peak amplitude of similar kinds have also been found in other ERP studies on cognitive aging (e.g., Friedman, Kazmerski, & Fabiani, 1997). Even though the functional and neuroanatomical factors contributing to the modified P3 topography in the elderly are still a matter of debate, a speculative interpretation for the flattened P3 topography and the enhanced general switch costs in the word task could be that the older adults recruit frontal areas to a larger extent for the more demanding implementation of the task set of the word task (cf. Milham et al., 2002).

The CNV was 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 for the color or for the word task. In contrast, older adults showed a substantially larger CNV under switching conditions, suggesting that maintaining of task

[4] An ANOVA including *only the single tasks* indicated a significant interaction effect between age group and task type, $F(1,26) = 5.55$, $p < .05$, suggesting that responding to the word task was much faster than responding to the color task for older as compared to younger adults.

sets was different in single- and mixed-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 maintaining the currently relevant task set under mixed-task conditions. Another possible interpretation of the late CNV effect would be that it reflects response expectation or engagement in motor preparation processes (Dirnberger et al., 2000; Jonkman, Lansbergen, & Stauder, 2003; van Boxtel & Brunia, 1994). In this framework our findings would suggest that older adults are engaged in motor preparation to a larger extent in switching conditions than under single-task conditions. Additional research will be necessary to distinguish between the maintenance and motor preparation account for the age effects in the late CNV.

ERP Correlates of Interference Control

The analyses of ERPs in the target interval allowed us to additionally examine age-related differences in interference control during task execution. Most of the recent ERP studies found at least two ERP modulations in the target interval when subjects are confronted with incompatible Stroop tasks, a negativity, related to conflict detection, and a conflict SP, related to the resolution of conflict (Atkinson et al., 2002; Liotti et al., 2000; West, 2004; West & Alain, 2000).

The first noteworthy result is that Ni latency was slower for the color than the word task. This parallels the greater interference costs for the standard Stroop (color) task than for the reverse Stroop (word) task in the analyses of the behavioral data (see Table 1). The Ni was substantially slowed for older adults. Moreover, in mixed-task blocks this effect in the elderly subjects is more pronounced for the color than the word task, indicating that conflict processing is delayed for the elderly especially in the standard Stroop task.

A second important finding is that we obtained a larger Ni amplitude for incompatible than for compatible trials that was clearly present in both age groups. Moreover, the Ni was obtained in both tasks, supporting the view that the Ni component reflects general conflict processing that is required whenever a target stimulus involves ambiguous information (Liotti et al., 2000; Ruff et al., 2001; West & Alain, 2000). Thus, it appears that the Ni indicates a general mechanism of early conflict detection that is relatively invariant across tasks and age.

On the other hand, consistent with a prior study (Liotti et al., 2000), the Ni in the color task is broadly distributed across the scalp, whereas in the word task it appears to be more focused over anterior recording sites (see Figure 2). This indicates that the processes of interference control, as reflected by the Ni, are sensitive to the type of conflicting information (lexical information as in the color task or color information as in the word task; cf. Mecklinger, Weber, Gunter, & Engle, 2003; Milham et al., 2002).

In the response-locked ERPs of the younger adults, a frontocentrally distributed negativity (CRN) was obtained that was larger in amplitude for incompatible than for compatible trials. As no such compatibility effect was found for older adults (see Figure 3), this can be taken as evidence for age differences at this late and response-related stage of conflict processing. It is conceivable 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; Gehring, Goss, Coles, Meyer, & Donchin, 1993), 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 ERN in older adults (Falkenstein, Hoormann, & Hohnsbein, 2001; Gehring & Knight, 2000) 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 suggest that the CRN, similar to the ERN, reflects an age-related decline of the action monitoring system.

To summarize, this study provides new evidence for age differences in the time course and topography of ERP components associated with task preparation and conflict processing during task switching. The ERPs in the cue interval revealed age differences in the speed of updating of the currently relevant task set and in the neuronal processes mediating these processes as indexed by age modulations of P3 latency and scalp topography. Age-related differences in the CNV component may indicate that younger adults, to a larger extent than older adults, tend to maintain task settings until target presentation independently of switching conditions, probably to prevent interference from an irrelevant task set. An age-related delay in conflict detection was reflected in the slowing of Ni peak latency in the elderly. The presence of a CRN in the response-locked ERPs, in the younger adults only, further suggests that there were age differences in conflict processing even at a late and response-related processing stage.

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