Psychophysiology, 39 (2002), 100–110. Cambridge University Press. Printed in the USA.

DOI: 10.1017.S0048577201020042

Aging and the Simon task

ROB H.J. VAN DER LUBBE[a,b] AND ROLF VERLEGER[a]

[a]Department of Neurology, Medical University of Lübeck, Germany
[b]Psychological Laboratory, Helmholtz Institute, Utrecht University, The Netherlands

Abstract

A visual Simon task was used to study the influence of aging on visuospatial attention and inhibitory control processes. Responses were much slower for elderly than for young participants. The delay in trials in which stimulus and response side did not correspond as compared to when they did correspond (the Simon effect) was larger for older people, even after correcting for general slowing due to aging. The slowing of responses reflected a slowing of internal processing, as indicated by progressively larger delays of the peak latencies of the N1, the posterior contralateral negativity (PCN), and P3. A comparison between the amplitudes of the PCN and early lateralized readiness potential (pre-LRP) indicated that transmission from posterior sites (PCN) to the motor cortex may be affected by age. The data support the view that aging affects an inhibitory process that controls direct visuomotor transmission.

Descriptors: Aging, Simon task, Event-related potentials, Slowing, Inhibition

In the field of cognitive aging, many EEG studies focused on the effects of aging on event-related potential (ERP) components by using the Oddball task. Well-replicated findings with this task are a delay of ERP components due to aging, especially of the P3 component (for reviews, see Bashore, Osman, & Heffley, 1989; Polich, 1996). Effects on earlier components have also been reported, with the delay of components becoming progressively larger until the P3 (e.g., Czigler, Csibra, & Ambro, 1994; Verleger, Neukäter, Kömpf, & Vieregge, 1991). Besides effects on peak latencies, another well-known finding is the flattened topography of the P3 component for older people (i.e., a loss of the exclusive centroparietal focus; e.g., Friedman, Kazmerski, & Fabiani, 1997), which may be due to the loss of an overlap of frontal negativity (Anderer, Pascual-Marqui, Semlitsch, & Saletu, 1998; Pfefferbaum, Ford, Wenegrat, Roth, & Kopell, 1984). These findings can be easily related to current views on cognitive aging. That is, the progressive delay of several ERP components can be accounted for by general slowing (e.g., Myerson, Hale, Wagstaff, Poon, & Smith, 1990), whereas the change in topography of the P3 component may be due to functional changes of the frontal cortex (e.g., West, 1996). Nevertheless, the major focus on the Oddball task may imply that important aspects of aging on memory, attention, and inhibitory control are underexposed.

Other paradigms have been used in which the main focus was on these aspects. Effects on memory were studied in a variety of tasks, using Sternberg's memory scanning task (e.g., Ford, Pfefferbaum, Tinklenberg, & Kopell, 1982; Lorist, Snel, Mulder, & Kok, 1995; Pelosi & Blumhardt, 1999), processing of complex sentences (Gunter, Jackson, & Mulder, 1995), continuous recognition (Friedman, Berman, & Hamberger, 1993), recognition and priming (Dywan, Segalowitz, & Webster, 1998; Mark & Rugg, 1998; Swick & Knight, 1997; Trott, Friedman, Ritter, & Fabiani, 1997), and cued recall (Friedman, Ritter, & Snodgrass, 1996). The influence of aging on visuospatial attention has been studied less extensively, with some studies on visual search (Looren de Jong, Kok, & van Rooy, 1988; Looren de Jong, Kok, Woestenburg, Logman, & van Rooy, 1988; Zeef & Kok, 1993), and some with cueing paradigms (Curran, Hills, Patterson, & Strauss, 2001; Yamaguchi, Tsuchiya, & Kobayashi, 1995). Likewise, the number of studies focusing on inhibitory control is also small, with some studies on the Eriksen flanker task (Zeef & Kok, 1993; Zeef, Sonke, Kok, Buiten, & Kenemans, 1996), and variants of the Stroop task (Christensen, Ford, & Pfefferbaum, 1996; West & Alain, 2000).

The Simon task has been studied extensively in experimental psychology, and seems well suited to study the influence of aging on both visuospatial attention and inhibitory control. In addition, as far as we know, no ERP study on aging has been performed with this task. In the fully visual version of the Simon task, mostly two stimuli are used (in the current task we use the letters A and B). Participants are instructed to respond with their left hand in case of one stimulus (here an A), and with their right hand in case of the other stimulus (here a B). The stimuli are presented to the left or right of fixation, and consequently, the side of presentation may correspond with the required response side (corresponding trials) or not (noncorresponding trials). In general, reaction times (RT) are faster for corresponding than for noncorresponding trials: the

Rob van der Lubbe was supported by a grant from the Deutsche Forschungs-gemeinschaft to Rolf Verleger (110/7-1 and 110/7-2) and a grant from the Dutch Organization for Fundamental Research (NWO: 440-20-000). We thank Alexandra Wessel for her help in the recruitment of participants and collecting the data, and we thank Judith Ford and two anonymous reviewers for their stimulating comments on earlier versions of the manuscript.

Address reprint requests to: Rob H.J. van der Lubbe, Psychological Laboratory, Utrecht University, Heidelberglaan 2, 3584 CS Utrecht, The Netherlands. E-mail: r.vanderlubbe@fss.uu.nl.

Simon or correspondence effect (for reviews, see Hommel, 2000; Lu & Proctor, 1995; Simon, 1990). In our study, a version of this task was used in which opposite to the letter a neutral stimulus is presented (cf. Grice, Boroughs, & Canham, 1984). This procedure can be used to prevent exogenous lateralization in the ERPs (Valle-Inclán, 1996), and the magnitude of the Simon effect remains the same with this variation (Hommel, 2000; Wascher, Schatz, Kuder, & Verleger, 2001).

An interesting electrophysiological measure that can be obtained in this task is the posterior negativity contralateral to the side of the letter, which peaks at about 250 ms after stimulus onset (Wascher & Wauschkuhn, 1996). This component has its maximum near the PO7 and PO8 electrodes (see multichannel maps in Wascher et al., 2001, and Praamstra & Plat, 2001) and was first described by Luck and Hillyard (1994) as the N2pc (posterior contralateral). The component can be considered as a correlate for discrimination of the relevant stimulus (Eimer, 1996; Wauschkuhn et al., 1998), which probably occurs as a function of visuospatial attention (Luck, Girelli, McDermott, & Ford, 1997; Van der Lubbe & Woestenburg, 2000; Woodman & Luck, 1999). Wascher and Wauschkuhn (1996) displayed this component as the contraipsilateral difference to the relevant response hand, extending the method described by Coles (1989) for the lateralized readiness potential (LRP) to include posterior electrodes. By doing this, it becomes easier to relate this component to the LRP (see also Praamstra & Plat, 2001; Wascher, Reinhard, Wauschkuhn, & Verleger, 1999; Wascher et al., 2001) and to measure its peak latency (Wauschkuhn et al., 1998). The amplitude and latency of this component varies independently of the N2 ERP component (Shedden & Nordgaard, 2001); therefore, using the name N2pc seems misleading. In the current article we decided to adopt the name posterior contralateral negativity (PCN), which is similar to the N2pc, but does not suppose a relation with the N2. As already mentioned, the PCN component is considered to be specific for discrimination or selective processing of the relevant stimulus. The amplitude of the PCN indicates to what extent this discrimination takes place and its latency gives temporal information about this discrimination process.

Interestingly, some recent studies examined the relation between the amplitude of the PCN and the simultaneous lateralization above central brain areas (Wascher & Wauschkuhn, 1996). The latter lateralization may be viewed as preactivation of motor areas, similar to the description of Gratton, Coles, Sirevaag, Eriksen, and Donchin (1988) for the Eriksen flanker paradigm (see also in case of Simon-like tasks in De Jong, Liang, & Lauber, 1994; Masaki, Takasawa, & Yamazaki, 2000; Valle-Inclán, 1996; Valle-Inclán & Redondo, 1998), and may be characterized as the pre-LRP. Praamstra and Plat (2001) and Wascher et al. (2001) suggested that the amplitudes of the PCN and the pre-LRP may be indicative for transmission along a direct visuomotor pathway (e.g., see Roelfsema, Engel, König & Singer, 1997; Tanné, Boussaoud, Boyer-Zeller, & Rouiller, 1995). For example, a reduction of the pre-LRP relative to the PCN in a specific condition may indicate that direct transmission in that condition became smaller.

Most interestingly, it has been proposed that direct visuomotor transmission increases when inhibitory control decreases, which may occur due to the use of different task instructions (Wascher et al., 2001), but also due to Parkinson's disease (see Praamstra & Plat, 2001). In this line, direct visuomotor transmission might also change due to aging. The inhibition deficit hypothesis of Hasher and Zacks (1988) proposes that age-related impairments result from a weakening of inhibitory processes with age. Thus, aging may be accompanied by increased direct visuomotor transmission showing up in larger transmission of the activity reflected by PCN to the pre-LRP. In other words, the amplitude of the pre-LRP relative to the amplitude of the PCN may be larger for elderly than for young participants.

The inhibition deficit hypothesis of Hasher and Zacks (1988) corresponds with the view that functions supported by prefrontal cortex decline at an earlier age than those supported by other brain areas (West, 1996). Indeed, some studies provided support for decreased inhibitory control in older people (e.g, West & Alain, 2000; Zeef & Kok, 1993; Zeef et al., 1996), but other studies found no differences between young participants and older people (Christensen et al., 1996; Simon & Pouraghabagher, 1978).

For instance, Christensen et al. (1996) reported that the stimulus-response compatibility effect on RT and P3 latency did not depend on age in their visual Stroop-like task. However, West and Alain (2000) provided support for the inhibition-deficit hypothesis. They found that the Stroop effect on reaction time (RT) was larger for elderly than for young participants, even after correcting for the general slowing of responding.[1] In addition, amplitude modulations reflecting the inhibition of word information on incongruent trials increased with age. Thus, the results with Stroop-like tasks seem somewhat equivocal. Perhaps these studies differed in the amount of practice given to participants, which may affect the magnitude of the Stroop effect (Rabbitt, Lowe, & Shilling, 2001). This problem plays no role in the Simon task as it has been shown that the correspondence effect is a persistent phenomenon that remains even after several days of practice (Simon, 1990).

An examination of the influence of aging in a version of the Simon task with irrelevant auditory directional cues and centrally presented visual stimuli was already reported by Simon and Pouraghabagher (1978; see also Simon, 1990). They found no evidence for differences in inhibitory control between young and older people as the Simon effect was unaffected by age (26 ms for young participants and 27 ms for older participants) although old participants reacted much slower than young participants. However, their results perhaps cannot be generalized to visual stimuli. There may be major differences between the visual and the auditory version of this task as indicated by the results of Wascher et al. (2001). First, with a fully visual version, the Simon effect decreases when responses are slower, which has been ascribed to a decay of spatial codes formed at stimulus onset (De Jong et al., 1994; Hommel, 1994). Importantly, this decrease did not occur with an auditory version or with a crossed-hands version of the visual task. Second, effects on the pre-LRP differed between both versions, with earlier motor activation in case of the visual version. Third, the influence of crossing the hands appeared to be of no importance for the auditory version, in contrast to the visual version. According to our view, an important difference between a fully visual version and the hybrid auditory–visual version used by Simon and Pouraghabagher concerns the task relevance of the directional cue. That is, the auditory directional cue appears to have no relevance for the task with centrally presented targets, whereas the position of the letter in the fully visual version is

[1]To estimate on the basis of RT data whether age has an effect on specific processes, the possibility has to be excluded that the interaction between a variable ascribed to a specific process and age is simply due to general slowing (Salthouse, 1985). Therefore most recent behavioral studies employed a procedure to correct for general slowing (see Methods section).

relevant for attentional orienting as the target randomly appears to the left or right side of fixation.

In the current examination of a fully visual version of the Simon task, we expected that older people would respond more slowly than young participants, as was also found in the hybrid variant used by Simon and Pouraghabagher (1978). Because the relevance of position might be higher in the present fully visual version of the task than in that study, the Simon effect might become larger for elderly than for young participants, which may be ascribed to a decrease of inhibitory control in the older people. In addition, we examined whether there is a difference between elderly and young participants in the decrease of the Simon effect as a function of response speed, which has been related to a decay of spatial codes (see De Jong et al., 1994; Hommel, 1994; Wascher et al., 2001). In accordance with most ERP studies on aging, we expected to find a delay of the P3 component, and also of the earlier N1 component. In addition, amplitude of the P3 component may be flattened for older people, due to the loss of an overlap of frontal negativity, whereas a more pronounced centroparietal focus may be expected for young participants. We were especially interested in the influence of aging on the PCN and on the magnitude of the Simon effect. We hypothesized that three effects may occur due to aging. First, the amplitude of the PCN may be reduced in older people due to less efficient discrimination between the relevant and the irrelevant stimulus. Second, the PCN may be delayed in older people as a reflection of slowed attentional processing, similar to the intraindividual delay in case of less salient stimuli (Wauschkuhn et al., 1998). This delay of the PCN may be comparable with the observed delay of other ERP components, but can be interpreted more easily as it is location specific. Third, simultaneously with the PCN, a pre-LRP should be observed. The amplitude of the pre-LRP relative to the amplitude of the PCN may be larger for elderly than for young participants due to increased direct visuomotor transmission resulting from a weakening of inhibitory processes. Finally, the start and duration of correct motor activation may also be affected by age (Band & Kok, 2000), which may also differ as a function of correspondence due to changes in the efficiency of inhibitory control. This can be examined by performing a stimulus-locked (s) and response-locked (r) analysis of the LRP.

Methods

Participants

Thirteen elderly participants, recruited by an advertisement in a local newspaper in Lübeck, and 12 young participants, recruited from the local student population, cooperated in our experiment. The data of 1 young and 2 elderly participants had to be removed due to too many EEG artefacts. This left an old group (1 female, age 61.2 $\pm$ 8.8 years) and a young group (3 female, age 25.2 $\pm$ 2.8 years) each consisting of 11 participants. All participants had normal or corrected to normal vision, and reported no history of neurological disorder, which in case of the older people was assessed in a prior verbal questionnaire.

Stimuli and Procedure

Participants were seated in a comfortable armchair in a separate chamber. Visual stimuli were presented on a 14-in. Multisync monitor with an observation distance of approximately 1.2 m. Stimulus presentation was controlled by a PC.

A trial started with a white fixation cross (0.6° $\times$ 0.6°) displayed in the center of the monitor on a black background accompanied by two symmetrically positioned white frames (1.0° $\times$ 0.8°), centered at 1.3° to the left and right of the fixation cross. Next, after an interval varying between 1,000 and 2,250 ms, one frame was filled with a yellow letter (A or B) and the other frame was filled with three horizontal yellow bars that were similar to the letters in size and luminance. After 200 ms, the screen was cleared for 1,800 ms. Then the next trial started. The side (left or right) and identity of the letter (A or B) varied randomly from trial to trial, all with an equal probability of 25% (A left, A right, B left, B right).

Task

The task consisted of 600 trials. After every 100 trials a short pause was given. Participants were instructed to press the left button when an A was presented and the right button when a B was presented. Thus, the side of the stimulus and the required response side could correspond (correspondence trials) or not (noncorrespondence trials). Participants were instructed to respond as fast and accurately as possible.

Recording and Data Processing

EEG was recorded from Ag/AgCl electrodes (Picker-Schwarzer), located at F3, Fz, F4, FC3, FC4, C3′ (1 cm in front of C3), C1, Cz, C2, C4′ (1 cm in front of C4), P7, P3, Pz, P4, P8, PO7, O1, O2, and PO8, referred to an electrode affixed at the nose. EOG was recorded bipolarly both vertically from above and below the left eye (vEOG) and horizontally from the outer canthi of both eyes (hEOG). EEG and EOG were amplified and filtered by a Nihon-Kohden 4421 amplifier (TC = 5.0 s, lowpass 70 Hz). Electrode resistance was kept below 10 kΩ. Response force was recorded continuously from isometric weight elements that had to be pressed by the two index fingers. A trigger sent from a control computer started data sampling on a second computer (EEG, EOG, and response force) at a rate of 200 Hz from 195 ms before to 2,400 ms after the imperative stimulus. Trials with zero lines, out-of-scale values, slow drifts larger than 80 μV, and fast shifts larger than 120 μV/500 ms were excluded from further analyses (which left 74.8% and 88.8% of the trials for the young and older participants, respectively).

The transmission of vEOG and of hEOG into the EEG was estimated separately in areas of maximum EOG variance. EEGs were corrected by subtracting both EOG channels weighted by their transmission coefficient (see Verleger, Gasser, & Möcks, 1982). Finally, a low-pass filter with a cut-off frequency of 17.6 Hz (Ruchkin & Glaser, 1978) was applied.

Data Analysis

Response parameters. RT was defined as the moment when response force crossed the criterion of 2 N and was averaged across left- and right-hand responses. Errors included trials with forces $>$ 2 N of both hands (one correct, one wrong: "corrected errors"), with forces $>$ 2N of the incorrect hand only ("full errors"), premature responses (faster than 150 ms), and responses slower than 1,500 ms. Trials with forces in between 0.5 and 2 N of the incorrect hand (partial errors) that were followed by a correct response with a force larger than 2 N, and responses with a force larger than 2 N of the correct hand and no force exerted by the incorrect hand larger than 0.5 N were defined as correct responses. The error trials were excluded from the RT and EEG analyses.

Response force was defined as the maximum value of force output for correct trials. The mean RTs, the different proportions (full errors, corrected errors, premature responses, misses, slow

responses, partial errors, and fully correct responses), and response force were evaluated statistically by analysis of variance (ANOVA) with the between-subjects factor age (young vs. old) and the repeated-measurements factor correspondence (corresponding vs. noncorresponding). Several authors have argued that the global slowing effect of age on RT is most adequately described by an exponential increase (e.g., see Kray & Lindenberger, 2000; Mayr, 2001; Van Asselen & Ridderinkhof, 2001), which may be corrected for by taking the natural logarithm of RT. This transformation was applied on RTs to examine whether the possible interaction between correspondence and age is solely due to general slowing.

Several studies indicated that the correspondence effect becomes smaller when responses are slower, which has been ascribed to a decay of spatial codes (e.g., De Jong et al., 1994; Hommel, 1994; Wascher et al., 2001). A distribution (quintiles) analysis was performed per condition for each group on RTs to examine whether we could replicate this result and, more interestingly, whether this decrease differed as a function of age. We estimated the time points (bins) at which 20%, 40%, 60%, and 80% of the reactions (from fast to slow) had occurred to obtain values for the different levels of the post hoc variable speed. The 0% and 100% time points are defined by the criteria we used to exclude misses and premature responses and were therefore not used in the analysis. Greenhouse–Geisser epsilon correction was performed to adjust the degrees of freedom whenever possible.

EEG parameters. ERPs were computed for all electrodes by averaging EEGs for all trials with correct responses without artefacts. This was done separately for corresponding and noncorresponding trials for both age groups. Amplitudes were referred to a baseline from −95 to 0 ms before presenting the imperative stimulus. More details about the analyses performed on the ERP data are reported in the Results section.

Contra-ipsilateral difference potentials (ERLs) were calculated separately for each symmetrical electrode pair (F3/4, FC3/4, C3′/4′, C1/2, P3/4, P7/8, PO7/8, O1/2) the same way as the LRP is computed. That is, for right-hand responses, activity (averaged across trials) at the right electrode was subtracted from activity at the left electrode, and for left-hand responses, activity at the left electrode was subtracted from activity at the right electrode. These two differences were then averaged to yield the general difference contralateral minus ipsilateral relative to response side (Coles, 1989). Thus, a negative difference wave indicates that activity is more negative at the site contralateral to the required movement side than ipsilateral. Both stimulus-locked and response-locked analyses (referred to the prestimulus baseline aligned either to stimulus onset or to the response) were performed. For the analyses of the PCN, amplitudes were computed relative to the relevant stimulus side.

Our interest was focused on effects of age and correspondence on the peak latency and amplitude of the PCN, and the start of the PCN, the s-LRP, and the r-LRP. In addition, we determined the relation between the PCN and the simultaneous anterior lateralization above hand motor areas (pre-LRP) to examine the influence of age on direct visuomotor transmission (see Praamstra & Plat, 2001; Wascher et al., 2001). Amplitudes were determined for several time windows of 25 ms, based on inspection of grand means, to examine whether the PCN started earlier for young than for older people. The same analysis was performed for the start of the s-LRP and the r-LRP to examine whether there was an effect of age, and whether the correspondence effect differed as a function of age. In the latter analyses, lateralized activity of the electrode pair at which the PCN was most pronounced was used as a covariate to control for possible volume conduction effects from posterior sites (see Van der Lubbe & Woestenburg, 1999).

Results

Behavioral Measures

Mean RTs, response force, proportions of fully correct responses, partial errors, corrected errors, full errors, misses, and too slow responses, all as a function of age and correspondence, are presented in Table 1.

First, we will focus on the different types of incorrect behavior. No fast guesses were observed. There were less fully correct responses in noncorrespondence than in correspondence trials, $F(1,20) = 21.9$, $p < .001$. Partial errors, $F(1,20) = 21.1$, $p < .001$, as well as corrected errors, $F(1,20) = 9.4$, $p = .006$, and full errors, $F(1,20) = 8.6$, $p = .008$, occurred more often in noncorrespondence than in correspondence trials. Misses occurred very infrequently, possibly also due to too weak responding, somewhat more often for correspondence than for noncorrespondence trials, $F(1,20) = 6.7$, $p = .017$, whereas no effect on too slow responses was found. Importantly, in all these analyses there were no effects of age nor any interaction between age and correspondence, $F(1,20) < 1.7$.

RTs were faster for corresponding trials (526 ms) than for noncorresponding trials (560 ms), $F(1,20) = 62.9$, $p < .0001$.

Table 1. *Mean RTs (in Milliseconds), Response Force (in Newtons), Proportions of Fully Correct Responses, Partial Errors, Corrected Errors, Full Errors, Misses, and Too Slow Responses as a Function of Age (Young vs. Old) for Corresponding (Corr) and Noncorresponding (Nonc) Trials*

	RT	Force	Fully correct	Partial error	Corrected error	Full error	Misses	Too slow
Young								
Corr	477	16.4	96.3	1.3	1.3	0.7	0.3	0.1
Nonc	497	16.5	92.1	3.7	2.6	1.2	0.2	0.1
Old								
Corr	575	16.8	97.6	0.5	0.3	0.5	0.6	0.5
Nonc	623	17.2	91.1	2.8	3.3	1.4	0.4	0.8

Young participants reacted much faster than old participants, by an amount of 112 ms, $F(1,20) = 9.7$, $p = .006$. The effect of correspondence was larger for the older group (48 ms) than for the young group (20 ms), $F(1,20) = 10.8$, $p = .004$. This interaction between correspondence and age remained significant when RTs were ln-transformed, $F(1,20) = 6.7$, $p = .017$, and thus cannot be accounted for by general slowing.

The results of the distribution analysis on RTs are presented in Figure 1. Apart from the already reported effects and the effect of dividing into RT bins, the analysis revealed that the correspondence effect interacted with speed, $F(3,60) = 7.5$, $\epsilon = .44$, $p < .007$, decreasing from 43 ms for the 20% bin to 41 ms for the 40% bin, to 37 ms for the 60% bin, and to 26 ms for the 80% bin. Contrast analyses revealed that the correspondence effect for the 80% bin was significantly smaller than for the 60% bin, $F(1,20) = 12.3$, $p = .002$. The effect of age interacted with speed, $F(3,60) = 4.9$, $\epsilon = .36$, $p = .035$, increasing from 93 ms for the 20% bin to 102 ms for the 40% bin, to 113 ms for the 60% bin, to 125 ms for the 80% bin. Contrast analyses revealed that the effect of age was smaller for the 20% bin than for the 40% bin, $F(1,20) = 4.8$, $p = .04$, and smaller for the 40% bin than or the 60% bin, $F(1,20) = 6.9$, $p = .02$. No second-order interaction was found between Age, RT bin, and correspondence, $F(3,60) < 0.3$.

Response force was smaller for correspondence (16.6 N) than for noncorrespondence trials (16.9 N), $F(1,20) = 9.5$, $p = .006$. Although the results in Table 1 suggest that the difference in force between correspondence and noncorrespondence trials was larger for elderly than for young participants, no effect of age, and no interaction between age and correspondence was found, $F(1,20) < 1.9$.

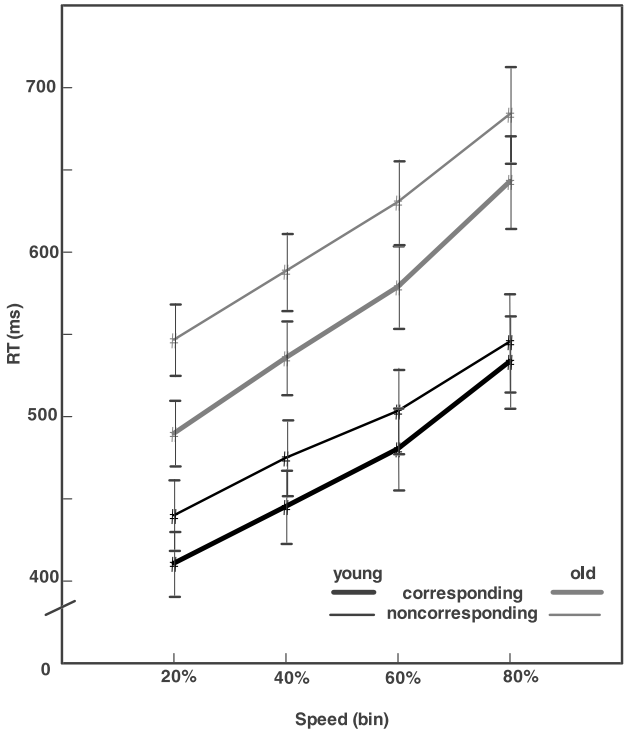

Figure 1. RTs as a function of response speed in bins (20%, 40%, 60%, and 80%) for correspondence and noncorrespondence trials for young and old participants. The vertical bars indicate the standard errors.

ERPs

ERPs from all electrodes are displayed in Figure 2. No major differences are visible as a function of correspondence whereas the influence of age is reflected in a global delay of the entire ERP waveform, beginning at the posterior N1 component. Closer inspection reveals that this shift is initially more posterior and later more frontocentral. Because such a shift of the entire waveshape is not easy to quantify, we decided to simply use the posterior N1 and the centroparietal P3 as "landmarks," measuring the shift at these peaks. This is not meant to imply that it is precisely these components that are shifted; rather the shift might well be an underlying trend on which these components are riding.

The N1 component. The latency and amplitude of the N1 component was measured at all posterior electrodes as the most negative peak in the average ERP per participant within a window from 160 to 300 ms after stimulus onset. ANOVAs were performed with the within-subject factors electrode (4) and hemisphere (2) (i.e., (P3, P7, PO7, O1) and (P4, P8, PO8, O2)), correspondence (2), and the between-subjects factor age (2). For N1 latency, there was a main effect of age, $F(1,20) = 12.7$, $p = .002$, which indicated that the N1 component peaked earlier for young participants (187 ms) than for older people (215 ms). Other effects were not significant.

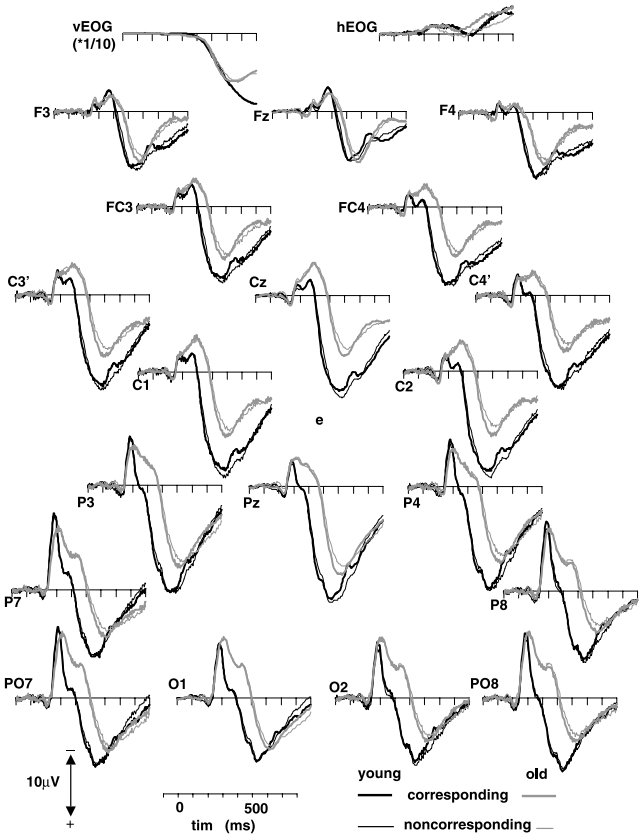

Figure 2. ERPs for all electrodes displayed for correspondence and noncorrespondence trials for young and old participants. Along the abscissa we indicated the time (t) in milliseconds from −100 to 800 ms after stimulus onset.

For N1 amplitude, there was an effect of electrode, $F(3,60) = 33.7$, $\epsilon = .60$, $p < .001$, an interaction between electrode and age, $F(3,60) = 4.5$, $\epsilon = .60$, $p = .021$[2] and an interaction between correspondence and hemisphere, $F(1,20) = 8.6$, $p < .008$. Inspection of Figure 2 suggests that the Electrode × Age interaction may be due to the reduced N1 amplitude at the O1 and O2 electrodes relative to the other electrodes for young participants but not for older people. This suggestion was confirmed by still obtaining an interaction between age and electrode, $F(1,20) = 4.7$, $p = .043$, after having reduced the electrodes entering analysis to PO7, O1, PO8, and O2. The interaction between correspondence and hemisphere reflected that N1 was less negative at the left than at the right hemisphere in case of correspondence (-10.0 vs. -10.2 μV), and behaved the opposite way in case of noncorrespondence, (-10.1 vs. -9.8 μV). This very small effect is not visible in Figure 2, and seems difficult to interpret.

The P3 component. For the analyses of the P3 component, we selected the F3, Fz, F4, C3, Cz, C4, P3, Pz, and P4 electrodes to reduce the levels of independent variables while still retaining a global picture of the effects on P3. Peak latency and amplitude were assessed at the most positive peak within a window of 320 to 700 ms. ANOVAs were performed with the within-subjects factors correspondence (2), left-right axis (left, midline, right), anterior–posterior axis (frontal, central, parietal), and the between-subjects factor age.

The analysis on P3 latency revealed that the P3 component peaked earlier for correspondence (489 ms) than for noncorrespondence trials (514 ms), $F(1,20) = 31.4$, $p < .001$, and earlier for young participants (468 ms) than for older people (535 ms), $F(1,20) = 6.3$, $p = .02$. The correspondence effect was independent of age, $F(1,20) < 0.01$. We found an interaction between anterior–posterior axis and age, $F(2,40) = 5.5$, $\epsilon = .63$, $p = .02$, and an interaction between anterior–posterior axis, left–right axis, and age, $F(4,80) = 4.8$, $\epsilon = .59$, $p = .009$. A contrast analysis revealed that the frontal-central difference differed between young participants and older people, $F(1,20) = 7.7$, $p = .01$. Namely, peak latency was the same for frontal and central sites for young participants (476 vs. 475 ms), but P3 peaked much later for older people at central sites (555 ms) than at frontal sites (496 ms). An additional analysis suggests that the frontal-central difference for older people was smaller at the left hemisphere (518 vs. 549 ms) than at the midline (483 vs. 558 ms), $F(1,20) = 6.7$, $p = .02$, whereas no difference between the midline and the right hemisphere (487 vs. 557 ms) was found, $F(1,20) < 0.1$.

The analyses on P3 peak amplitude showed that amplitudes increased along the anterior–posterior axis, $F(2,40) = 45.2$, $\epsilon = .76$, $p < .001$. P3 amplitude tended to be smaller for elderly (10.5 μV) than for young participants (15.3 μV), $F(1,20) = 3.6$, $p = .07$. Contrast analyses revealed that the frontal P3 (9.3 μV) was smaller than the central P3 (13.3 μV), $F(1,20) = 56.5$, $p < .001$, and the central P3 was again smaller than the parietal P3 (16.1 μV), $F(1,20) = 16.5$, $p = .001$. This effect seemed to be larger for young participants than for older people, $F(2,40) = 4.2$, $\varepsilon = .76$, $p = .03$. However, after applying the rescaling procedure (see footnote 2) the interaction between anterior–posterior axis and age was no longer significant, $F(2,40) = 2.2$. An interaction was found between anterior–posterior and left–right axis, $F(4,80) = 9.5$, $\epsilon = .69$, $p < .001$, trivially due to anterior–posterior effects being larger on the midline than on the left and also larger on the midline than on the right. Potentially of more interest, we observed an interaction between correspondence, left–right axis and age, $F(2,40) = 5.4$, $\epsilon = .86$, $p = .012$, which remained significant after applying the rescaling procedure, $F(2,40) = 5.2$, $\epsilon = .86$, $p = .014$. For young participants, P3 amplitude was more positive for noncorrespondence trials than for correspondence trials, which effect was largest along the midline (15.8 vs. 15.3 μV) whereas for older people, P3 amplitude was less positive for noncorrespondence trials than for correspondence trials, this effect again being largest along the midline (10.5 vs. 11.2 μV).

ERLs

The mean stimulus-locked lateralizations for all symmetrical electrode pairs are presented in Figure 3 as a function of required response side. The LRP is well visible at central and frontal sites. At posterior sites, a contra-ipsilateral difference is visible. Being inverted for noncorresponding trials, this difference is evidently determined more by stimulus side than by response side.

The posterior contralateral negativity (PCN). We determined the peak amplitude (relative to relevant stimulus side, i.e., by inverting the noncorrespondence waveforms relative to the way they are presented in Figure 3) and latency of the PCN as the most negative peak within 200–350 ms at all four posterior electrode pairs (P3/4, P7/8, PO7/8, O1/2). ANOVAs were performed with

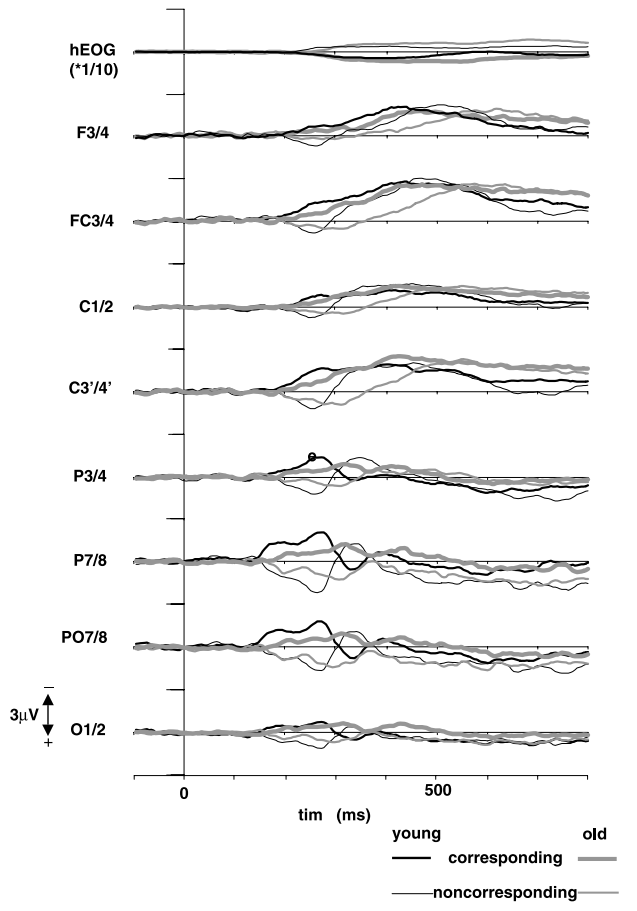

Figure 3. Stimulus-locked ERLs for correspondence and noncorrespondence trials for young and old participants for all symmetrical electrode pairs. Along the abscissa we indicated the time (t) in milliseconds from -100 to 800 ms after stimulus onset.

[2]This interaction remained significant after correcting for differences in source strength between both groups, $F(3,60) = 6.6$, $\varepsilon = .68$, $p = .003$, using vector-normalization (McCarthy & Wood, 1985).

the factors electrode pair (4), correspondence (2), and age (2). The main ANOVA showed that the peak of the PCN occurred earlier for young participants (263 ms) than for older people (293 ms), $F(1,20) = 5.2$, $p = .034$. We performed a separate analysis for the P7/8 electrode pair, as the PCN (see the amplitude results) was most pronounced at that site. The analysis confirmed that the PCN peaked earlier for young participants (263 ms) than for older people (297 ms), $F(1,20) = 5.7$, $p = .027$. No other effects on peak latency were observed.

Regarding the peak amplitude of the PCN, we found only an effect of electrode pair, $F(3,60) = 19.6$, $\varepsilon = .67$, $p < .001$. The PCN was larger at the P7/8 electrode pair (-2.4 μV) than at the P3/4 electrode pair (-1.5 μV), $F(1,20) = 24.0$, $p < .001$, and larger at the PO7/8 electrode pair (-2.0 μV) than at the O1/2 electrode pair (-1.2 μV), $F(1,20) = 36.4$, $p < .001$, with no difference between the PO7/8 and the P7/8 electrode pairs, $F(1,20) = 0.4$. No effect of age was found, $F(1,20) = 1.4$, $p = .25$, although PCN amplitude (see Figure 3) seemed larger for young (-2.0 μV) than for elderly participants (-1.6 μV).

Lateralization of the PCN may start earlier for young participants than for older people. The amplitude for 25-ms time windows (4), as a function of correspondence (2), was determined from 125 until 225 ms after stimulus onset for the P7/8 electrode pair. The analysis showed that negativity increased over time, $F(3,60) = 13.3$, $\varepsilon = .54$, $p < .001$, but this effect was not different between age groups, $F(3,60) = 1.4$. An almost significant effect of age was found, $F(1,20) = 4.2$, $p = .055$, which reflects the larger amplitude of the PCN for young (-0.7 μV) than for elderly participants (-0.2 μV). The latter results provide some support for an earlier start of the PCN in young than in the older people.

Relating the PCN with the pre-LRP. To examine direct visuomotor transmission, we determined the relation between the peak amplitude of the PCN (relative to the relevant stimulus side) as obtained for the P7/8 electrode pair, and the simultaneous lateralization at the C3/4 electrode pair. An ANOVA was performed with the factors electrode pair (2), correspondence (2), and the between-subjects factor age (2). Lateralization at the C3/4 electrode pair (-1.4 μV) was reduced as compared to the P7/8 electrode pair (-2.3 μV), $F(1,20) = 34.7$, $p < .001$. Some support was found for the hypothesis that this effect differed between young and elderly participants, $F(1,20) = 4.0$, $p = .06$. For young participants, amplitude decreased from -2.7 to -1.5 μV, and for elderly participants, amplitude decreased from -2.0 to -1.4 μV.

The s-LRP. Lateralization of the stimulus-locked LRP was analyzed for intervals determined after inspection of the grand means (see Figure 3). Activity at the P7/8 electrode pair (where the PCN was largest) was used as covariate to control for volume conduction effects from posterior sites (see Van der Lubbe & Woestenburg, 1999).[3] An initial analysis showed that there were large differences between correspondence and noncorrespondence trials (see Figure 3), for 12 25-ms time windows from 150 to 450 ms after stimulus onset, $F(1,19) = 9.0$, $p = .008$, and negativity increased over time, $F(11,219) = 28.8$, $p < .001$. Separate analyses were performed for correspondence and noncorrespondence trials.

For correspondence trials, an analysis was performed for 25-ms time windows from 150 to 300 ms after stimulus onset. No main effect of age was found, $F(1,19) = 2.5$, $p = .129$, but the included covariate proved to be significant, $F(1,19) = 6.9$, $p = .016$. An analysis without inclusion of the covariate showed a main effect of age, $F(1,20) = 7.9$, $p = .011$. Negativity was larger for young (-1.0 μV) than for elderly participants (-0.3 μV) The analysis including the covariate revealed a main effect of time, $F(5,99) = 17.9$, $p < .001$, but no interaction between age and time, $F(5,99) = 1.3$, was found.

For noncorrespondence trials, an analysis was performed for the interval from 275 to 450 ms after stimulus onset. No earlier lateralization for young participants than for older people was observed, $F(1,19) = 2.6$, $p = .123$, but the included covariate was again significant, $F(1,19) = 6.8$, $p = .018$. An analysis without the covariate showed a main effect of age, $F(1,20) = 5.4$, $p = .03$. Negativity was larger for young (-1.3 μV) than for elderly participants (0.01 μV). The analysis including the covariate also revealed an effect of time, $F(6,119) = 15.4$, $p < .001$. No interaction between age and time was found, $F(6,119) = 0.8$.

Thus, the absence of significant effects of age for the s-LRP, although these effects are clearly present in Figure 3, can be ascribed to simultaneous effects at posterior sites.

The r-LRP. Response-locked lateralizations as a function of correspondence for both age groups for the C3′/4′ and the P7/8 electrode pair are displayed in Figure 4. Averages for time windows of 25 ms were computed per participant from 275 until

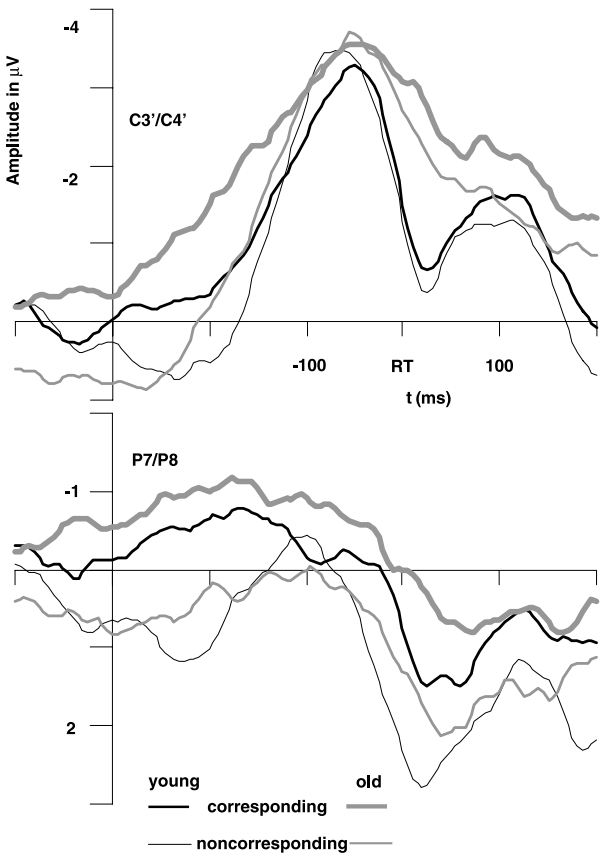

Figure 4. The response locked LRP (r-LRP) and simultaneous lateralization at the P7/8 electrode pair as a function of correspondence for young and old participants. Along the abscissa we indicated the time (t) in milliseconds from -400 to 200 ms after the response.

[3]Greenhouse–Geisser ϵ correction could not be used because SPSS could not provide an estimate when the covariate was included.

100 ms before responding to examine whether the initial difference in polarity as a function of correspondence (2) decreased as a function of time (7), and whether effects were dependent on age (2). Activity at the P7/8 electrode pair was again included as a covariate. Negativity increased (see Figure 4) when the time interval was nearer to the response, $F(6,119) = 60.1$, $p < .001$. A main effect of correspondence was found, $F(1,19) = 7.1$, $p = .015$, and this effect decreased when the time interval was nearer to the response, $F(6,119) = 7.2$, $p < .001$.

For correspondence trials, the development over time was not significantly different as a function of age (Age × Time, $F(6,119) = 1.3$) and no main effect of age (only a weak trend) was found, $F(1,19) = 2.8$, $p = .11$. The included covariate was not significant, $F(1,19) = 0.1$. An analysis without inclusion of the covariate revealed a trend to an effect of age, $F(1,20) = 3.4$, $p = .08$. Amplitudes were more negative for elderly (-1.7 μV) than for young participants (-1.0 μV).

For noncorrespondence trials, no main effect of age was found, $F(1,19) = 1.5$, but the covariate proved to be significant, $F(1,19) = 9.2$, $p = .007$. No interaction between age and time was found, $F(6,119) = 1.7$, $p = .13$. An analysis without inclusion of the covariate also revealed no effect of age, $F(1,20) = 0.6$, and the development over time also did not differ as a function of age, $F(6,120) = 1.2$.

Thus, no convincing evidence was found for the effect of age on the r-LRP.

Discussion

A fully visual version of the Simon task was used to examine the influence of aging on visuospatial attention and inhibitory control. First, we will focus on the main effects of aging on RTs and ERPs. Then, we will discuss effects on the PCN, which can be related to visuospatial attention. Next, we will consider the relation between the amplitudes of the PCN and the pre-LRP, which has been related to inhibitory control, and will deal with changes in the magnitude of the Simon effect. Finally, we will focus on age-specific effects on the start of motor activation as indexed by the s-LRP and on the duration of motor processing as indexed by the r-LRP, and response force.

Delayed RTs and the Shifts of ERPs for Older People

A conspicuous result of the present study was the massive shift of the older participants' ERPs (see Figure 2), associated with the large difference in response times. Young participants reacted about 100 ms faster than the older people, even in correspondence trials, which is comparable to the difference as observed in the hybrid version of the Simon task used by Simon and Pouraghabagher (1978). This effect is much larger than the difference usually obtained in auditory and visual oddball tasks. This difference has often been nonsignificant (e.g., Czigler, Csibra, & Ambró, 1996; Ford & Pfefferbaum, 1991; Friedman, Simpson, & Hamberger, 1993; Picton, Stuss, Champagne, & Nelson, 1984; Polich, 1997; Verleger et al., 1991) even in visual choice-response tasks (Dujardin, Derambure, Bourriez, Jacquesson, & Guieu, 1993; Looren De Jong, Kok, & Van Rooy, 1989). One exception is the study by Podlesny, Dustman, and Shearer (1984), where a reliable 70-ms difference was obtained in a go/no-go task with simple symbols (X vs. O). Usually, however, as is well known in aging research (Myerson et al., 1990; Salthouse, 1985), a certain amount of complexity was needed to obtain reliable response-time differences. Thus, somewhat surprisingly, replacing simple visual stimuli by words in oddball-like go/no-go or two-choice tasks is apparently sufficient to obtain reliable response-time differences (Christensen et al., 1996; Pfefferbaum & Ford, 1988; Smulders, Kenemans, Schmidt, & Kok, 1999; Tachibana, Aragane, & Sugita, 1996; tendency in Verleger et al., 1991).

The older people's shift of ERPs as displayed in Figure 2 looks unusual. A view to the literature, as partially quoted in the preceding paragraph, provides the reason underlying this impression. Apparently, such a shift can be obtained only in the presence of reliable differences in response times, which is not the case in simple oddball-type studies (cf. above). Our interpretation and measurement of these shifts as delay of the N1 and P3 components (like Lorist et al., 1995) is preliminary. Alternatively these shifts might be described as reflecting underlying slow waves (cf. Podlesny et al., 1984) with the late anterior shift perhaps being related to the late "post-retrieval" frontal positivity which is currently investigated intensively in relation to memory operations (e.g., Mark & Rugg, 1998; Nessler, Mecklinger, & Penney, 2001). Alternatively, it might reflect the lack of frontal negativity that has been proposed to account for the age difference of P3 topography in oddball studies (cf. the introduction).

In line with other ERP studies on aging, we observed a delay of the P3 for older people, and we also observed a delay of the P3 in case of noncorrespondence trials as usually found in the Simon task (see review by Verleger, 1997, p. 140). In addition, an effect of correspondence was found on P3 amplitude, being largest along the midline, but the effect was different for young participants and older people. P3 amplitude became larger for young participants on noncorrespondence trials, whereas it became larger for older people on correspondence trials. This result indicates that there are qualitatively different effects as a function of age; however, we can only guess about an interpretation for this reversal.

The Posterior Contralateral Negativity (PCN)

Both for young participants and for the older people the PCN was largest at the P7/8 electrode pair (see Figure 3). No effect of aging was found on the peak amplitude of the PCN, but some support was found that the PCN started later for older people. The peak of the PCN was reached earlier for young participants than for older people. Thus, there is some evidence that discrimination starts later or is less efficient for older people, and the moment at which discrimination is most pronounced is reached later for older people.

Interestingly, in the S1-S2 task used by Yamaguchi et al. (1995), no age-related differences were found in the effects of validity of peripheral and symbolic cues on RTs in a simple-response task. These findings support the view that attentional processes are not vulnerable to aging (however see Curran et al., 2001; Madden, Gottlob, & Allen 1999). In addition, the PCN-like component observed by Yamaguchi et al. (1995), a larger negativity evoked by the S1 at posterior sites contralateral to the symbolically cued direction was also not affected by age. This discrepancy with the results of the PCN in our study may be due to several reasons. For instance, the relevance of the timing of attentional orienting in an S1-S2 task may be small, making it difficult to find an effect of age. In addition, in the task of Yamaguchi et al., the relevance of orienting itself was also less because the S2 had to be detected only. Finally, it is also possible that the ERL component in the S1-S2 study of Yamaguchi et al. simply reflects a process different from the PCN because the former was evoked by the cueing S1, and the latter by the imperative stimulus. Thus, on the basis of our results of the peak latency of the PCN, it may be concluded that the moment at which discrimination is most pronounced is delayed in

older people. This might be one of the reasons for the dramatic delay of their response times.

Inhibitory Control

To study the influence of aging on inhibitory control, we focused on an index for direct visuomotor transmission and the Simon effect. The proportion of lateralization above the primary motor areas (pre-LRP) relative to the lateralization above extrastriate brain areas (PCN) was almost significantly affected by age. Thus, the inhibitory process that plays a role in the control of direct visuomotor transmission might be affected by age. The Simon effect was much larger for elderly than for young participants, even after applying a method to correct for differences in speed. Thus, both RT and the amplitude of the pre-LRP relative to the peak of the PCN might reflect the same age-related reduction of inhibitory processing.

The increased Simon effect for older people in our study contrasts with the findings of Simon and Pouraghabagher (1978). We argued already in our introduction that there are important differences between a visual and a hybrid auditory-visual version. That is, we ascribe the discrepancy with Simon and Pouraghabagher to the higher relevance of the spatial stimulus code in a fully visual version of the Simon task, which probably is related to attentional orienting. The distribution analysis on RTs replicated that the Simon effect in a visual version of the task decreases when responses are slower (De Jong et al., 1994; Hommel, 1994; Wascher et al., 2001). This finding can be ascribed to a decay of the spatial stimulus code formed at stimulus onset. The effect of age became larger for slower reactions, which indicates that variability in responding was larger for older people, which is not surprising. More interestingly, the decrease of the Simon effect was independent of age, which suggests that there is no effect of age on the decay of the spatial code itself.

Effects on Motor Processes

Another issue to be addressed was whether we could replicate the increased duration of motor processing for older people as reported by Band and Kok (2000). The start of motor activation as indexed by the s-LRP seems to be affected by age (see Figure 3). However, after correction for simultaneous activation at posterior sites, this effect was no longer significant. If the activity at motor sites is solely due to volume conduction, then it could be concluded that the start of motor activation was not affected by age. However, on the basis of the results from some recent studies (e.g., Oostenveld, Praamstra, Stegeman, & Van Oosterom, 2001; Van der Lubbe, Jaśkowski, Wauschkuhn, & Verleger, 2001) it may be argued that volume conduction plays no important role. In that case, it could be argued that our findings indicate that motor activation started later for older people. The influence of aging on the duration of motor processes, the time interval between the start of motor activation and the final response, was examined by using the r-LRP. For correspondence trials, the covariate was not significant, and thus should not be included in the analysis. After exclusion of the covariate, some weak support was found for the hypothesis that the time interval was prolonged by age. However, for noncorrespondence trials, no such effect was found. Thus, only weak support was found for an increased duration of motor processes as reported by Band and Kok (2000).

An interesting finding is that response force was somewhat larger for noncorrespondence trials than for correspondence trials, replicating one of our previous studies (Wascher, Verleger, & Wauschkuhn, 1996; see also Van der Lubbe et al., 2001), although no effect was found in other studies (Wascher & Wauschkuhn, 1996; Wascher et al., 2001). The larger force may be related to the effects of expectancy on response force in an S1-S2 paradigm (Ja[/]skowski, Van der Lubbe, Wauschkuhn, Wascher, & Verleger, 2000). In that study, force became larger when S1 was an invalid response cue. It may be proposed that this invalid response cue can be equated with the noncorresponding position of the imperative stimulus in the Simon task. Finally, no effect of age was found on response force. In combination with the results of other studies showing weaker force in case of a more conservative response strategy in conditions with low time pressure (Jaśkowski et al., 2000), and an increase of the correspondence effect on RT in case of a more liberal response strategy (Van der Lubbe et al., 2001), it may be suggested that there were no major differences in strategy as a function of age. This suggestion is also supported by the absence of age effects on error proportions in the current study.

Conclusions

In conclusion, a massive shift in ERPs was found for older people that seems related to the large RT difference between both age groups. Early processes related to attentional orienting, as reflected in N1 and PCN components, were already delayed in older people. Some evidence was found for decreased inhibitory control along a direct visuomotor pathway, which may explain the increased Simon effect for older people. Finally, only weak support was found for the view that the duration of motor processes was delayed for older people.

REFERENCES

Anderer, P., Pascual-Marqui, R. D., Semlitsch, H. V., & Saletu, B. (1998). Differential effects of normal aging on sources of standard N1, target N1 and target P300 auditory event-related brain potentials revealed by low resolution electromagnetic tomography (LORETA). *Electroencephalography and Clinical Neurophysiology*, *108*, 160–174.

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

Bashore, T. R., Osman, A., & Heffley, E. F., III (1989). Mental slowing in elderly persons: A cognitive psychophysiological analysis. *Psychology and Aging*, *4*, 235–244.

Christensen, C., Ford, J. M., & Pfefferbaum, A. (1996). The effect of stimulus-response incompatibility on P3 latency depends on the task but not on age. *Biological Psychology*, *44*, 121–141.

Coles, M. G. H. (1989). Modern mind-brain reading: Psychophysiology, physiology, and cognition. *Psychophysiology*, *26*, 251–269.

Curran, T., Hills, A., Patterson, M. B., & Strauss, M. E. (2001). Effects of aging on visuospatial attention: An ERP study. *Neuropsychologia*, *39*, 288–301.

Czigler, I., Csibra, G., & Ambró, Á. (1994). Event-related potentials and aging: Identification of deviant visual stimuli. *Journal of Psychophysiology*, *8*, 193–210.

Czigler, I., Csibra, G., & Ambró, Á. (1996). Aging, stimulus identification and the effect of probability: An event-related potential study. *Biological Psychology*, *43*, 27–40.

De Jong, R., Liang, C., & Lauber, E. (1994). Conditional and unconditional automaticity: A dual-process model of effects of spatial stimulus-response Correspondence. *Journal of Experimental Psychology: Human Perception and Performance*, *20*, 731–750.

Dujardin, K., Derambure, P., Bourriez, J. L., Jacquesson, J. M., & Guieu, J. D. (1993). P300 component of the event-related potentials (ERP) during an attention task: Effects of age, stimulus modality and event probability. *International Journal of Psychophysiology*, *14*, 255–267.

Dywan, J., Segalowitz, S. J., & Webster, L. (1998). Source monitoring: ERP evidence for greater reactivity to nontarget information in older adults. *Brain and Cognition*, *36*, 390–430.

Eimer, M. (1996). The N2pc as an indicator of attentional selectivity. *Electroencephalography and Clinical Neurophysiology*, *99*, 225–234.

Ford, J. M., & Pfefferbaum, A. (1991). Event-related potentials and eyeblink responses in automatic and controlled processing: Effects of age. *Electroencephalography and Clinical Neurophysiology*, *78*, 361–377.

Ford, J. M., Pfefferbaum, A., Tinklenberg, J. A., & Kopell, B. S. (1982). Effects of perceptual and cognitive difficulty on P3 and RT in young and old adults. *Electroencephalography and Clinical Neurophysiology*, *54*, 311–321.

Friedman, D., Berman, S., & Hamberger, M. (1993). Recognition memory and ERPs: Age-related changes in young, middle-aged, and elderly adults. *Journal of Psychophysiology*, *7*, 181–201.

Friedman, D., Kazmerski, V., & Fabiani, M. (1997). An overview of age-related changes in the scalp distribution of P3b. *Electroencephalography and Clinical Neurophysiology*, *104*, 498–513.

Friedman, D., Ritter, W., & Snodgrass, J. G. (1996). ERPs during study as a function of subsequent direct and indirect memory testing in young and old adults. *Cognitive Brain Research*, *4*, 1–13.

Friedman, D., Simpson, G., & Hamberger, M. (1993). Age-related changes in scalp topography to novel and target stimuli. *Psychophysiology*, *30*, 383–396.

Gratton, G., Coles, M. G. H., Sirevaag, E. J., Eriksen, C. W., & Donchin, E. (1988). Pre- and post-stimulus activation of response channels: A psychophysiological analysis. *Journal of Experimental Psychology: Human Perception and Performance*, *14*, 331–344.

Grice, G. R., Boroughs, J. M., & Canham, L. (1984). Temporal dynamics of associative interference and facilitation produced by visual context. *Perception & Psychophysics*, *36*, 499–507.

Gunter, T. C., Jackson, J. L., & Mulder, G. (1995). Language, memory, and aging: An electrophysiological exploration of the N400 during reading of memory-demanding sentences. *Psychophysiology*, *32*, 215–229.

Hasher, L., & Zacks, R. T. (1988). Working memory, comprehension and aging: A review and a new view. In G. G. Bower (Ed.), *The psychology of learning and motivation* (vol. 22, pp. 193–225). San Diego, CA: Academic Press.

Hommel, B. (1994). Spontaneous decay of response code activation. *Psychological Research*, *56*, 261–268.

Hommel, B. (2000). Intentional control of automatic stimulus-response translation. In Y. Rossetti & A. Revonsuo (Eds.). *Interaction between dissociable conscious and nonconscious processes* (pp. 223–244). Amsterdam: John Benjamins Publishing Company.

Jaśkowski, P., Van der Lubbe, R. H. J., Wauschkuhn, B., Wascher, E., & Verleger, R. (2000). The influence of time pressure and expectancy on response force in an S1-S2 paradigm. *Acta Psychologica*, *105*, 89–105.

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

Looren De Jong, H., Kok, A., & Van Rooy, J. C. G. M. (1988). Early and late selection in young and old adults: An event-related potential study. *Psychophysiology*, *25*, 657–671.

Looren De Jong, H., Kok, A., & Van Rooy, J. C. G. M. (1989). Stimulus probability and motor response in young and old adults: An ERP study. *Biological Psychology*, *29*, 125–148.

Looren De Jong, H., Kok, A., Woestenburg, J. C., Logman, C. J. C. M., & Van Rooy, J. C. G. M. (1988). Learning where to look: Electrophysiological and behavioral indices of visual search in young and old subjects. *Biological Psychology*, *26*, 277–298.

Lorist, M. M., Snel, J., Mulder, G., & Kok, A. (1995). Aging, caffeine and information processing: An event-related potential analysis. *Electroencephalography and Clinical Neurophysiology*, *96*, 453–467.

Lu, C.-H., & Proctor, R. W. (1995). The influence of irrelevant location information on performance: A review of the Simon and spatial Stroop effects. *Psychonomic Bulletin & Review*, *2*, 174–207.

Luck, S. J., Girelli, M., McDermott, M. T., & Ford, M. A. (1997). Bridging the gap between monkey neurophysiology and human perception: An ambiguity resolution theory of visual selective attention. *Cognitive Psychology*, *33*, 64–87.

Luck, S. J., & Hillyard, S. A. (1994). Electrophysiological correlates of feature analysis during visual search. *Psychophysiology*, *31*, 291–308.

Madden, D. J., Gottlob, L. R., & Allen, P. A. (1999). Adult age differences in visual search accuracy: Attentional guidance and target detectability. *Psychology and Aging*, *14*, 683–694.

Mark, R. E., & Rugg, M. D. (1998). Age effects on brain activity associated with episodic memory retrieval. An electrophysiological study. *Brain*, *121*, 861–873.

Masaki, H., Takasawa, N., & Yamazaki, K. (2000). An electrophysiological study of the locus of the interference effect in a stimulus-response compatibility paradigm. *Psychophysiology*, *37*, 464–472.

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.

Myerson, J., Hale, S., Wagstaff, D., Poon, L. W., & Smith, G. A. (1990). The information-loss model: A mathematical theory of age-related cognitive slowing. *Psychological Review*, *97*, 475–487.

Nessler, D., Mecklinger, A., & Penney, T. B. (2001). Event related brain potentials and illusory memories: The effects of differential encoding. *Cognitive Brain Research*, *10*, 283–301.

Oostenveld, R., Praamstra, P., Stegeman, D. F., & Van Oosterom, A. (2001). Overlap of attention and movement-related activity in lateralized event-related brain potentials. *Clinical Neurophysiology*, *112*, 477–484.

Pelosi, L., & Blumhardt, L. D. (1999). Effects of age on working memory: An event-related potential study. *Cognitive Brain Research*, *7*, 321–334.

Pfefferbaum, A., & Ford, J. M. (1988). ERPs to stimuli requiring response production and inhibition: Effects of age, probability and visual noise. *Electroencephalography and Clinical Neurophysiology*, *71*, 55–63.

Pfefferbaum, A., Ford, J. M., Wenegrat, B. G., Roth, W. T., & Kopell, B. S. (1984). Clinical application of the P3 component of event-related potentials. I. Normal aging. *Electroencephalography and Clinical Neurophysiology*, *59*, 85–103.

Picton, T. W., Stuss, D. T., Champagne, S. C., & Nelson, R. F. (1984). The effects of age on human event-related potentials. *Psychophysiology*, *21*, 312–325.

Podlesny, J. A., Dustman, R. E., & Shearer, D. E. (1984). Aging and respond-withhold tasks: effects on sustained potentials, P3 responses and late activity. *Electroencephalography and Clinical Neurophysiology*, *58*, 130–139.

Polich, J. (1996). Meta-analysis of P300 normative aging studies. *Psychophysiology*, *33*, 334–353.

Polich, J. (1997). EEG and ERP assessment of normal aging. *Electroencephalography and Clinical Neurophysiology*, *104*, 244–256.

Praamstra, P., & Plat, F. M. (2001). Failed suppression of direct visuomotor activation in Parkinson's disease. *Journal of Cognitive Neuroscience*, *13*, 31–43.

Rabbitt, P., Lowe, C., & Shilling, V. (2001). Frontal tests and models for cognitive ageing. *European Journal of Cognitive Psychology*, *13*, 5–28.

Roelfsema, P. R., Engel, A. K., König, P., & Singer, W. (1997). Visuomotor integration is associated with zero time-lag synchronization among cortical areas. *Nature*, *385*, 157–161.

Ruchkin, D. S., & Glaser, E. M. (1978). Simple digital filters for examining CNV and P300 on a single-trial basis. In D. Otto (Ed.), *Multidisciplinary perspectives in event-related brain potential (ERP) research* (pp. 579–581). Washington DC: U.S. Government Printing Office.

Salthouse, T. A. (1985). *A theory of cognitive aging*. Amsterdam: North Holland.

Shedden, J. M., & Nordgaard, C. L. (2001). ERP time course of perceptual and post-perceptual mechanisms of spatial selection. *Cognitive Brain Research*, *11*, 59–75.

Simon, J. R. (1990). The effects of an irrelevant directional cue on human information processing. In R. W. Proctor & T. G. Reeve (Eds.), *Stimulus-response compatibility: An integrated perspective* (pp. 31–86). Amsterdam: North Holland.

Simon, J. R., & Pouraghabagher, A. R. (1978). The effect of aging on the stages of processing in a choice reaction time task. *Journal of Gerontology*, *33*, 553–561.

Smulders, F. T. Y., Kenemans, J. L., Schmidt, W. F., & Kok, A. (1999). Effects of task complexity in young and old adults: Reaction time and P300 latency are not always dissociated. *Psychophysiology*, *36*, 118–125.

Swick, D., & Knight, R. T. (1997). Event-related potentials differentiate the effects of aging on word and nonword repetition in explicit and implicit memory tasks. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *23*, 123–142.

Tachibana, H., Aragane, K., & Sugita, M. (1996). Age-related changes in event-related potentials in visual discrimination tasks. *Electroencephalography and Clinical Neurophysiology*, *100*, 299–309.

Tanné, J., Boussaoud, D., Boyer-Zeller, N., & Rouiller, E. M. (1995). Direct

visual pathways for reaching movements in the macaque monkey. *NeuroReport*, *7*, 267–272.
Trott, C. T., Friedman, D., Ritter, W. & Fabiani, M. (1997). Item and source memory: Differential age effects revealed by event-related potentials. *NeuroReport*, *8*, 3373–3378.
Valle-Inclán, F. (1996). The locus of interference in the Simon effect: An ERP study. *Biological Psychology*, *43*, 147–162.
Valle-Inclán, F., & Redondo, M. (1998). On the automaticity of ipsilateral response activation in the Simon effect. *Psychophysiology*, *35*, 366–371.
Van Asselen, M., & Ridderinkhof, K. R. (2001). Shift costs of predictable and unexpected set shifting in young and older adults. *Psychologica Belgica*, *40*, 259–273.
Van der Lubbe, R. H. J., Jaśkowski, P., Wauschkuhn, B., & Verleger, R. (2001). Influence of time pressure in a simple detection task, a choice-by-location task, and the Simon task. *Journal of Psychophysiology*, *15*.
Van der Lubbe, R. H. J., Wauschkuhn, B., Wascher, E., Niehoff, T., Kömpf, D., & Verleger, R. (2000). Lateralized EEG components with direction information for the preparation of saccades versus finger movements. *Experimental Brain Research*, *132*, 163–178.
Van der Lubbe, R. H. J., & Woestenburg, J. C. (1999). The influence of peripheral cues on the tendency to react towards a lateral relevant stimulus with multiple-item arrays. *Biological Psychology*, *51*, 1–21.
Van der Lubbe, R. H. J., & Woestenburg, J. C. (2000). Location selection in the visual domain. *Psychophysiology*, *37*, 662–676.
Verleger, R. (1997). On the utility of P3 latency as an index of mental chronometry. *Psychophysiology*, *34*, 131–156.
Verleger, R., Gasser, T., & Möcks, J. (1982). Correction for EOG artifacts in event related potentials of the EEG: Aspects of reliability and validity. *Psychophysiology*, *19*, 472–480.
Verleger, R., Neukäter, W., Kömpf, D., & Vieregge, P. (1991). On the reasons for the delay of P3 latency in healthy elderly subjects. *Electroencephalography and Clinical Neurophysiology*, *79*, 488–502.
Wascher, E., Reinhard, M., Wauschkuhn, B., & Verleger, R. (1999). Spatial S-R compatibility with centrally presented stimuli: An event-related asymmetry study about dimensional overlap. *Journal of Cognitive Neuroscience*, *11*, 214–229.
Wascher, E., Schatz, U., Kuder, T., & Verleger, R. (2001). Validity and boundary conditions of automatic response activation in the Simon task. *Journal of Experimental Psychology: Human Perception and Performance*, *27*, 731–751.
Wascher, E., Verleger, R., & Wauschkuhn, B. (1996). In pursuit of the Simon effect: The effect of S-R compatibility investigated by event-related potentials. *Journal of Psychophysiology*, *10*, 336–346.
Wascher, E., & Wauschkuhn, B. (1996). The interaction of stimulus- and response-related processes measured by event-related lateralisations of the EEG. *Electroencephalography and Clinical Neurophysiology*, *99*, 149–162.
Wauschkuhn, B., Verleger, R., Wascher, E., Klostermann, W., Burk, M., Heide, W., & Kömpf, D. (1998). Lateralized human cortical activity for shifting visuospatial attention and initiating saccades. *Journal of Neurophysiology*, *80*, 2900–2910.
West, R. L. (1996). An application of prefrontal cortex function theory to cognitive aging. *Psychological Bulletin*, *120*, 272–292.
West, R., & Alain, C. (2000). Age-related decline in inhibitory control contributes to the increased Stroop effect observed in older adults. *Psychophysiology*, *37*, 179–189.
Woodman, G. F., & Luck, S. J. (1999). Electrophysiological measurement of rapid shifts of attention during visual search. *Nature*, *400*, 867–869.
Yamaguchi, S., Tsuchiya, H., & Kobayashi, S. (1995). Electrophysiologic correlates of age effects on visuospatial attention shift. *Cognitive Brain Research*, *3*, 41–49.
Zeef, E. J., & Kok, A. (1993). Age-related differences in the timing of stimulus and response processes during visual selective attention: Performance and psychophysiological analyses. *Psychophysiology*, *30*, 138–151.
Zeef, E. J., Sonke, C. J., Kok, A., Buiten, M. M., & Kenemans, L. J. (1996). Perceptual factors affecting age-related differences in focused attention: Performance and psychophysiological analyses. *Psychophysiology*, *33*, 555–565.

(Received September 7, 2000; Accepted August 14, 2001)