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RESEARCH NOTE

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Changes of error-related ERPs with age

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Abstract Errors in reaction tasks are followed by a negative component of the event-related brain potential (ERP), the error negativity (N_e), which is thought to be a correlate of error detection. In the present study we show that, in tasks that induce different types of errors, the amplitude of the N_e was reduced in elderly (54–65 years old) compared with young subjects (19–25 years old). This reduction was also seen in single trials, as were computed for one of the visual tasks. Moreover, in this data set, the single-trial N_e was also delayed for the elderly compared with the young. These data suggest an alteration of error detection in the elderly, which is only marginally reflected in performance.

Keywords Reaction tasks · Response monitoring · Errors · Error detection · Age

Introduction

Some years ago, we showed that different types of reaction errors are accompanied by two components of brain potentials (Falkenstein et al. 1990, 1991, 1995). The first of these is a phasic frontocentral negativity, which peaks shortly after the incorrect key press (error negativity, N_e). In 1990, we formulated the hypothesis that the N_e is a correlate of error detection in the sense of a mismatch between representations of the ongoing (erroneous) response and of the correct (i.e., required) response. In the following years, we (Falkenstein et al. 1997, 2000) as well as other groups (e.g., Gehring et al. 1993; Bernstein et al. 1995; Scheffers et al. 1996, who used the term error-related negativity, ERN, instead of N_e) provided evidence in support of the error-detection hypothesis. In the present report, we analyze the influence of age on the error negativity, N_e, and hence on the putative underlying process, namely error detection.

From everyday life observations, it appears that elderly people often react in a different way to errors than young people do. This suggests differences in error processing between elderly and young, which might be reflected in the N_e. In laboratory experiments, it has been shown that errors are usually corrected very quickly (Rabbitt 1966). Error correction may be based upon the comparison between representations of the executed and the correct response, i.e., error detection (Rabbitt 1968). For choice reaction tasks, Rabbitt (1979) found that elderly corrected their errors in a similar way as young, which suggests that also error detection is relatively unimpaired with age in such tasks. Hence, the question arises whether the N_e as a reflection of error detection also does not differ across young and old subjects in such tasks. In sum, the first issue of the present study is the investigation of age-related differences of the N_e.

A second issue of the present study is whether possible age effects on the N_e depend on the type of task. Particularly tasks that induce different error types are interesting in this respect. We used two different tasks to induce different kinds of errors, namely: (1) premature key presses forced by additional irrelevant stimuli; and (2) errors in which the wrong key is used despite the absence of irrelevant stimuli. In order to decide whether possible N_e differences are present in all single trials or rather reflect the absence of the N_e in a subset of trials, we analyzed the N_e not only in the averages, but also in single-error trials. In both tasks, time pressure was administered, which was aimed at enhancing the error rate and, hence, the amount of error-related brain potentials (ERPs).

A final issue concerned the dependence of a possible N_e age effect on the stimulus modality applied. We have shown earlier that the latency of the N_e relative to the error can, under certain conditions, depend on stimulus modality (Falkenstein et al. 1991, 1995). Hence, possible age-related N_e changes may differ across modalities as well. This was tested by using visual and auditory stimuli in one of the tasks. In sum, the present study ana-

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lyzed effects of age on error detection, as reflected in the error negativity (N_e), with type of error and stimulus modality as manipulated variables.

Materials and methods

Participants

Twenty-four healthy right-handed subjects participated in the study. Twelve of the subjects were young (six women; 19–25 years old, mean 22.5 years) and 12 were elderly (six women; 54–65 years, mean 58.3 years). All subjects gave their informed consent for participation, which was performed with the approval of the local ethics committee.

Tasks

Two different tasks were used; in one task, two stimulus modalities were applied in different blocks. The first task was a speeded four-alternative-choice reaction task (4-CR), which was aimed at inducing occasional reactions with the wrong finger ("incorrect choice" errors). In this task, single-letter stimuli (A, E, I, or O) were presented equiprobably with an interstimulus-interval of 1800 ms; in different blocks visual or auditory letters were used. The visual stimuli were presented in the center of a VDU screen at the fixation point; the auditory stimuli were presented diotically (same information at both ears) via headphones, which created a sound image centered in the head. Each letter had to be responded to with a specific finger (middle and forefinger of the left or right hand). Four blocks of 200 stimuli each were presented to each modality in this task.

The second task was a "Flanker task" (Eriksen and Eriksen 1974; Kopp et al. 1996), which was aimed at inducing premature incorrect responses to irrelevant stimuli. In this task, visual vertically arranged compound stimuli were presented with an interstimulus interval of 1600 ms. They consisted of a central arrowhead (target) presented in the center of the VDU, which pointed either to the right or to the left, and two adjacent arrowheads (flankers), which pointed either in the same (congruent condition) or in the opposite direction (incongruent condition) as the target. The flankers preceded the target by 100 ms in order to maximize premature responding to the flankers. The subjects had to react with the forefinger of the right or left hand, depending on the direction of the central arrowhead. Two blocks of 200 stimuli were presented in this task. Stimulus (target) duration was always 300 ms.

In both tasks, a moderate time pressure was administered by setting an RT limit (500 ms in the Flanker task and 700 ms in the 4-CR task). This was established by a feedback tone presented 1200 ms after the stimulus in trials in which the RT exceeded the limit; the feedback had to be avoided by the subjects. Both tasks were interspersed among other tasks. The first block of the Flanker task was presented shortly after the first block of the 4-CR task, the second block of the Flanker task was presented shortly before the fourth block of the 4-CR task. The subjects practiced the tasks on a separate training day until a stable performance was reached.

Data analysis

As behavioral variables, reaction time, error rate, and error correction rate were measured. The latter was defined as the percentage of correct key presses immediately after the error. The electroencephalogram (EEG) was recorded from 58 electrodes, including the lateral and vertical electrooculograms (EOG), with Cz as reference; eye-movement artifacts were removed by the method of Berg (Berg and Scherg 1994). From the EEG, response-Iocked ERPs were computed, beginning 200 ms before and ending 600 ms after the incorrect response, and re-referenced to average reference, i.e., the average voltage at all other electrodes. The ERP data were filtered digitally with a 17 Hz low-pass filter. The N_e was defined as the most negative peak at electrode FCz in the window 0–200 ms after the incorrect response. Its latency was measured relative to the incorrect key press, its amplitude relative to the preceding positivity (see below and Kopp et al. 1996).

Performance and N_e data were analyzed statistically by ANOVAs (BMDP 4V). In the 4-CR task, the factors were group (young, old), modality (visual, auditory), and block (1 to 4); in the flanker task, the factors were group and block (1, 2). In a supplementary ANOVA, the visual data of the 4-CR task (blocks 1 and 4) and the data of the flanker task were evaluated with the factors group, block, and task (4-CR, Flanker).

For the single-trial analysis (see below), 16 error epochs were chosen at random from the visual 4-CR task and filtered digitally with a 10 Hz low-pass filter. The N_e was measured as in the averaged data. Single-trial N_e amplitude and latency were evaluated statistically by BMDP 4V. The variances of single-trial N_e amplitude and latency were tested by Levene's test of variability, as implemented in BMDP (3D).

Results

Two subjects (a young and an elderly one) had to be excluded from the analysis because their total number of errors was too low (particularly for the auditory task).

4-CR task

The RT did not differ between correct (486 ms) and error trials (487 ms). It was longer for elderly (518 ms) than for young subjects (456 ms) [$F(1,20)=12.03$, $P=0.0024$]. The error rate was not significantly different between young (5.2%) and elderly (4.8%). However, it was larger after visual (5.8%) than after auditory (4.2%) stimuli [$F(1,20)=10.22$, $P=0.0045$]. The correction rate (CR) also did not differ significantly for young (65%) and elderly (59%). However, an age × modality interaction [$F(1,20)=5.95$, $P=0.0241$] indicated a lower CR after auditory (52%) than after visual (65%) stimuli for the elderly, while there was no modality difference for the young subjects (CR 65% in both).

In the response-locked averages (RTAs) of the error trials, the N_e was seen as a large bilateral symmetric negativity with maximum at FCz, peaking shortly after the error (Fig. 1). On correct trials, a smaller negativity ("CRN"; Ford 1999) was seen. Both components were preceded by a small positivity, which was used as baseline (cf. Methods section). To highlight the ERP differences between errors and correct responses, the error minus correct-difference waveshapes are also shown. For the elderly, the N_e appeared smaller and slightly delayed after visual stimuli, while the CRN amplitude showed no obvious age difference when measured relative to the preceding positivity (as we did for the N_e). It is also seen that the pre-response ERP was more negative for the young than for the old (relative to the pre-stimulus baseline), which underlines the importance of a pre-response baseline for measuring the N_e (such as the positivity we used). In the difference waveshapes, the age differences on the N_e appeared even larger than in the raw error traces. The N_e had a mean latency of 54 ms and a mean amplitude of –8.6 µV. It was, in fact, smaller for the

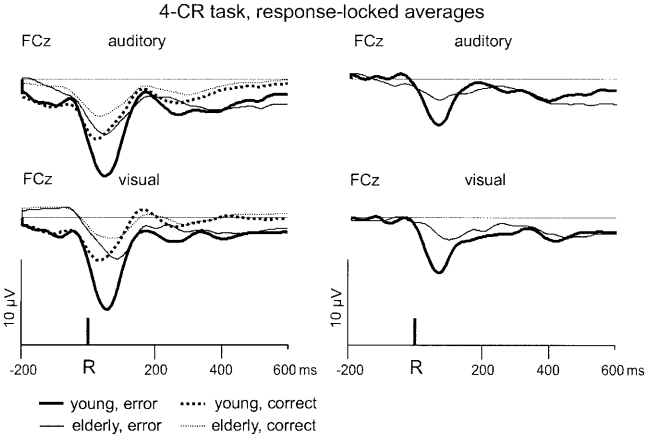

Fig. 1 Grand average of response-locked event-related brain potentials from FCz in the four-alternative-choice reaction (4-CR) task after incorrect responses (*straight lines*) and correct responses (*broken lines*) to auditory and visual stimuli for young subjects (*heavy lines*) and elderly subjects (*thin lines*). *Right panels* Incorrect-minus-correct difference waveshapes. *R* Key press. The *zero line* represents a pre-stimulus baseline of 200 ms

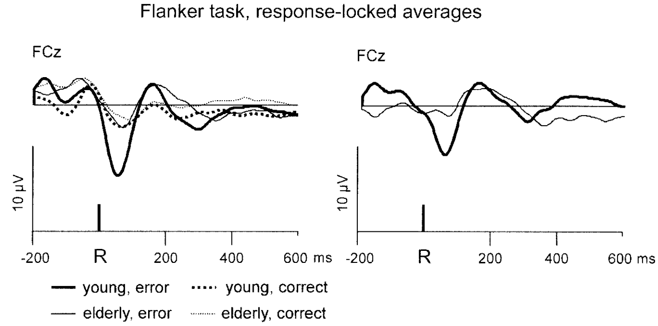

Fig. 2 Grand average of response-locked event-related brain potentials from FCz in the Flanker task after incorrect responses (*straight lines*) and correct responses (*broken lines*) for young subjects (*heavy lines*) and elderly subjects (*thin lines*). *Right panels* Incorrect minus correct difference waveshapes. (For details cf. legend of Fig. 1)

elderly (–6.5 µV) than for the young (–10.6 µV) [F(1,20)=5.70, P=0.0269]; the latency delay did not reach significance. Because of a tendencial age × modality interaction for N_e latency [F(1,20)=3.29, P=0.0848] simple effects were calculated for both modalities. After visual stimuli, the N_e tended to peak later for the elderly (70 ms) than for the young (53 ms) [F(1,20)=3.39, P=0.0806], while there was no latency difference between the groups after auditory stimuli. Generally, the N_e peaked later for visual (+61 ms) than for auditory stimuli (+47 ms) [F(1,20)=9.57, P=0.0057]. Moreover, it was larger for visual (–9.2 µV) than for auditory stimuli (–7.9 µV) [F(1,20)=4.75, P=0.0414]. The smallest N_e amplitude (–5.5 µV) was observed after auditory stimuli in elderly subjects.

Single-trial analysis

The N_e reduction for the elderly compared with the young, as seen in the averages, could be due to: (1) a genuine attenuation of the N_e in (almost) all single error epochs; (2) a larger-latency jitter of the N_e across epochs, which reduces the N_e amplitude in the averages, although it has the same amplitude as the young in the single epochs; and (3) the absence of the N_e in a certain proportion of the error epochs in the elderly, while having the same amplitude as the young in the remaining epochs. Possibility (2) should be reflected in a larger variance of N_e latency, possibility (3) in a larger variance of N_e amplitude in the elderly than in the young across the single epochs. The three possibilities were tested by measuring the N_e amplitudes of the visual 4-CR task in all single error epochs. The visual data were chosen because: (1) they yielded much more artifact-free error trials than the auditory data (so all 24 subjects could be tested), and (2) the significance of the delay of N_e latency for the elderly seen in the grand averages (Fig. 1) could be tested on the single trial level.

The single-trial ANOVA results revealed, in fact, smaller N_e amplitudes for the elderly (–8.9 µV) than for the young (–14.1 µV) [F(1,22)=10.36, P=0.0040] and also delayed N_e latencies in the elderly (76 ms) compared with the young (52 ms) [F(1,22)=9.07, P=0.0064). The standard deviation (SD) for N_e latencies was larger for the elderly (49 ms) than for the young (39) [Levene F(1,382)=11.24, P=0.0009], while the SD for N_e amplitudes was smaller for the elderly (4.8 µV) than for the young (8.1 µV) [Levene F(1,382)=42.75, P<0.0001].

Flanker task

The error rate was 17.7% for incongruent trials and 1.6% for congruent trials. There was no significant age effect on the incongruent error rate. Also the correction rate (CR) was not significantly different between elderly (43%) and young (63%), despite the large numerical difference. The mean RT (incongruent condition) was shorter for error trials (268 ms) than for correct trials (399 ms) [F(1,20)=469.4, P<0.0001]. It was longer for the elderly (359 ms) than for the young (308 ms) [F(1,20)=29.37, P<0.0001].

The N_e (as measured in the incongruent trials) had its maximum at FCz (Fig. 2). It had a mean latency of 61 ms after an incorrect response and a mean amplitude of –9.5 µV. As in the 4-CR tasks, the N_e was smaller for the elderly (–6.7µV) than for the young (–12.3 µV) [F(1,20)=5.61, P=0.0280]. The age difference on N_e latency (67 vs. 59 ms) did not reach significance. As in the 4-CR task, the CRN amplitude showed no age difference in the grand averages.

As expected, the combined ANOVA with the visual data of both tasks again resulted in a significant main effect of age on N_e amplitude [F(1,20)=5.10, P=0.0353]. There was no main effect of task and no group × task interaction (both F<1).

Discussion

The RT difference between incorrect and correct responses was not significant in the 4-CR task, while it was large (more than 100 ms) in the Flanker task (incongruent condition). This indicates that errors in incongruent Flanker-task trials were mainly premature responses to the flankers, which were presented 100 ms before the targets, while the errors in the 4-CR tasks were not due to premature responses.

Latency and amplitude of the N_e were virtually the same in both visual tasks. These results indicate that error detection, as reflected in the N_e, was similar in the two tasks, despite the different types of errors induced. The modality differences of N_e amplitude and latency suggest that the representation of the correct response (which is a prerequisite for the N_e) depends on stimulus modality in the present 4-CR task. Also, modality differences in the residual stimulus-related ERPs may have influenced the modality effect on N_e amplitude.

The most important result was the smaller amplitude of the N_e in the elderly than in the young in both tasks and for both modalities in the 4-CR task. The supplementary ANOVA showed that, for the visual data, this age effect was independent of the task. This difference is not an unspecific reflection of a general reduction of ERP amplitudes in the elderly: the other ERP components (which were also measured in both tasks, but not reported in detail above) showed no general amplitude reduction for the elderly. Also the CRN, as seen after correct responses, showed no general reduction in the elderly compared with the young.

At least for the visual 4-CR task, the N_e reduction in the elderly was also present (and even larger) on the single trial level. Moreover, the delay of N_e latency after visual stimuli, as seen in the averages, was highly significant in the single trials. Hence, the present results suggest that the process reflected in the N_e, i.e., error detection, is weakened (and sometimes also delayed) in the elderly in single error trials. The amplitude effect may be slightly enhanced in the averages by a larger latency variance in the elderly, but it is certainly not due to or enhanced by the absence of the N_e in the elderly in some of the trials, since the amplitude variance was lower in the elderly than in the young.

The finding that N_e amplitude and latency as well as the age effect on N_e amplitude were very similar for both visual tasks suggests that error detection as reflected in the N_e and its modification with age is independent of the task and the type of error.

A similar age effect on N_e amplitude has recently been reported by Band and Kok (2000), who used a visual mental-rotation task, which also supports this view. These authors also found decrements of the correction rate in the elderly in the most complex condition. In the present data set, we could show, in addition, that the N_e reduction with age is also present in easy tasks and for different types of errors.

In the present study, the N_e was also delayed relative to the response in the elderly, but only in the visual 4-CR task (single trials). This may be due to the relatively high difficulty of this task (as revealed from the error rates), which may in turn delay the representation of the correct response and, hence, the N_e for the elderly. Surprisingly, the age-related changes of the N_e were only marginally reflected in correction rate, which showed no main effect of age in both tasks. Hence, the assumed weakening of error detection in the elderly is possibly not strong enough to impair the immediate error correction considerably. However, in the 4-CR task, the condition with the smallest correction rate (elderly, auditory stimuli) showed also the smallest N_e. This might suggest that the error correction rate depends, at least to a certain degree, on the amplitude of the N_e. This is also compatible with the results of Band and Kok (2000). Since error correction is a robust phenomenon (Rabbitt 1966), it might be only affected when the N_e is particularly small, as observed for the elderly after auditory stimuli in the 4-CR task.

To summarize, the error negativity (N_e), an ERP component that is thought to reflect error detection, was significantly reduced in elderly compared with young subjects in two tasks that induce different type of errors. Moreover, in the more complex visual task, the N_e was delayed relative to the incorrect response for the elderly. These results may suggest an alteration of error detection in the elderly, which is only marginally reflected in a reduced error-correction rate.

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