Effects of task complexity in young and old adults

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Effects of task complexity in young and old adults: Reaction time and P300 latency are not always dissociated

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Abstract

Twelve young and 11 elderly men (mean ages 21.1 and 70.1) performed a choice-reaction time (RT) task in which stimulus degradation and stimulus–response (S-R) compatibility were manipulated. The extant literature has suggested that the effects of age on RT are usually augmented (multiplicative) in more difficult task conditions, but also that the effects of age on the latency of the P300 component of the event-related brain potential (ERP) are constant (additive). The results indicated that the effects of age on RT were enhanced in more difficult conditions, whether the difficulty consisted of stimulus degradation or S-R incompatibility. However, the effects of age on P300 latency were enlarged as the stimuli were degraded, but not if the S-R mapping was incompatible. Thus, it appears that task content determines if effects of age on P300 latency are additive or multiplicative. A simple model is proposed that produces the obtained pattern of effects.

Descriptors: Age differences, Reaction time, P300, Event-related potential, Stimulus–response compatibility, Stimulus degradation

It is a common observation that the speed of reactions is slower among elderly than among young subjects. Research in cognitive aging is concerned with the exact nature of this slowing process. In a simple yet straightforward approach, some researchers have tried to describe the relation between the reaction times (RTs) of the young and the elderly across a wide variety of tasks using linear regression analysis (Brinley, 1965; Cerella, 1985; Cerella, Poon, & Williams, 1980; Salthouse & Somberg, 1982), whereas others have used nonlinear regression techniques (Myerson, Hale, Wagstaff, Poon, & Smith, 1990). In both types of analysis the attempt is to describe the change in RT of older adults as a function of the change in RT of young adults as task complexity (defined operationally by RT) is increased. Thus, the RTs of the young were used as the predictor variable, and those of the elderly as the criterion variable.

The initial work in this domain was done using linear regression analysis. Any age-related delay in RTs that is constant across tasks of varying complexity was reasoned to be reflected in the intercept of the regression function. This delay represents the *additive* component of the effect of age that arises from a delay in peripheral sensorimotor processes, assuming that these processes were held constant across tasks (see discussion in Cerella, 1985). Any age-related delay that increases as tasks become more complex is reflected in the slope of the regression function. This delay represents the *multiplicative* component of effects of age that arises from a constant delay in every elementary processing step, with the number of these steps increasing with task complexity.[1]

The typical pattern of results in these analyses is that the slope of the regression function is larger than 1.0 (about 1.4) and the intercept approximates zero. The amount of variance explained by the linear function is generally high ($r^2 > .90$). Therefore, it has been concluded that effects of age are described accurately across a wide range of tasks by a single multiplicative function, and that all elements of central processing are affected by the same proportional amount (Cerella, 1985; Cerella et al., 1980; Salthouse, 1985a, 1985b; see review in Bashore, 1994). That is, cognitive

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[1]More complex functions than a simple multiplicative one may also apply, and have been proposed in the literature (e.g., Meyerson, Hale, Wagstaff, Poon, & Smith, 1990). Within the context of the present paper, however, it is sufficient to discriminate between additive functions, in which effects of age are constant, and functions that make effects of age increase with, for instance, task complexity. For simplicity, throughout the text, any function of the latter type will be labeled as "multiplicative," even though we realize that this term may not reflect the exact mathematical relation precisely.

slowing is argued to be a generalized phenomenon that affects all elements of processing to the same extent.

Bashore, Osman, and Heffley (1989) extended the above analyses of age-related decline in processing speed to include the latency of the P300 component of the event-related brain potential (ERP). The latency of the P300 component was used as an index of the time needed for stimulus processing that is relatively independent of (a) response processing demands (Duncan-Johnson & Donchin, 1982; Kutas, McCarthy, & Donchin, 1977; Magliero, Bashore, Coles, & Donchin, 1984; McCarthy & Donchin, 1981), and (b) the position taken on the speed-accuracy tradeoff function (Kutas et al., 1977). In one of their regression analyses, Bashore et al. selected studies that reported both RT and P300 latency data in the same tasks. The regression function for the RT data was linear ($r^2 = .87$), with a slope that was significantly larger than 1.0 (1.27) and an intercept that did not differ from zero. These values were in close correspondence to those that were reported in the literature and had been used to support the assertion that effects of age on RT are multiplicative. For P300 latencies, however, the slope did not differ from 1.0 and there was a significant positive intercept (90 ms). Thus, it was concluded that effects of age on P300 latency are additive, corresponding to what proponents of the regression approach would conclude is a peripheral sensorimotor deficit in the elderly. However, as noted by Bashore et al., P300 indexes the duration of not only peripheral, but also central processes. Therefore, they concluded that not all central processing is affected by advancing age. Specifically, the central processes involved in stimulus-related processing were argued to be less sensitive to the effects of aging than those involved in response-related processing.

A different line of evidence points in the same direction as these meta-analyses on RT and P300 latency. Using a Sternberg (1966) memory scanning task, Ford, Roth, Mohs, Hopkins, and Kopell (1979) studied the effects of increasing memory set size on these two measures of processing speed in young and older subjects. First, they found that effects of age on RT increased as memory set size increased, indicating the contribution of a multiplicative aging component. Second, they found that whereas P300 latency increased with memory load in both groups, the effect of age was invariant across memory set sizes, indicating a purely additive aging component. This pattern, a multiplicative effect on RT, in combination with an additive effect on P300 latency, resembles the results of Bashore et al. (1989). From their data, Ford et al. concluded that the rate of memory scanning itself, indexed by P300 latency, is not affected by aging but that the proportional increase of RT was due to the elderly experiencing an increasing lack of confidence in more difficult task conditions, leading to a delay in response-related processes that affect only RT, not the latency of the P300.

Both lines of evidence for a dissociation between effects of age on P300 latency and RT are problematic, however. First, there have been recurrent debates on the validity of the regression approach to describe the effects of aging on mental processing speed, especially in meta-analytic studies (e.g., Cerella, 1991, 1994; Fisk & Fisher, 1994; Fisk, Fisher, & Rogers, 1992; Fisk & Rogers, 1991; Kliegel & Mayr, 1992; Myerson, Wagstaff, & Hale, 1994; Perfect, 1994; Salthouse, 1992; Schaie, 1992). It has been argued that a high amount of variance explained by a linear regression function is misleading as an indicator of a single task-independent proportional slowing factor, because high explained variance can also be obtained in simulated data sets developed explicitly to include multiple task-dependent slowing factors (Perfect, 1994). As a consequence, also in empirical data the simple regression analysis may not be sensitive to cases in which the slowing factor depends on the task content. Second, the morphology of the P300 recorded in the Sternberg memory scanning task by Ford et al. (1979) may have been distorted in a manner leading to a bias in its latency estimate. Okita, Wijers, Mulder, and Mulder (1985) and Wijers, Otten, Feenstra, Mulder, and Mulder (1989) have measured gross changes in the amplitude and scalp distribution of the late components of the ERP as memory load is increased in this task. These changes were thought to be produced by an amplitude increase in a negative component (identified as the "search negativity") that is broadly distributed across the scalp and overlaps temporally with the P300.

Although it has been argued that changes in P300 amplitude can be dissociated from the search negativity (Mecklinger, Kramer, & Strayer, 1992; Scheffers & Johnson, 1994), the extent to which estimates of P300 latency are biased by this search negativity remains unclear. However, indications of such a bias have been reported to be strong, and always in the direction of an underestimation of the true latency (Looren de Jong, Kok, & Van Rooy, 1988; Pelosi, Hayward, & Blumhardt, 1995). A figure in Kok (1988) clarifies how overlap between a negative wave and P300 may lead to an underestimation of P300 latency. This underestimation may be a particular problem among the elderly because the search negativity is thought to reflect an effortful, controlled processing mode (Okita et al., 1985). It is easy to imagine that elderly individuals have to invest more effort in the memory scanning task in order to maintain their performance and this increased effort produces an increase in the amplitude of the negative wave. This increased negative wave amplitude may, in turn, lead to a larger underestimation of P300 latency in the elderly than in the young, changing a potentially overadditive interaction between age and memory set size effects into an additive effect.[2] In conclusion, the inevitable overlap of a negative component and the P300 in tasks with a variable memory load may bias estimates of P300 latency and lead to a misinterpretation of age-related effects on this measure.

We followed Ford et al. (1979) in using a set of task conditions that was based on the additive factor method (Sternberg, 1969) to study effects of age. Instead of loading the memory search process, however, the difficulty of stimulus encoding and the stimulus–response (S-R) mapping were manipulated. Visual degradation of the stimuli was expected to increase the duration of stimulus encoding. Manipulations such as stimulus discriminability and stimulus degradation are known to have robust effects on P300 latency (Magliero et al., 1984; McCarthy & Donchin, 1981, 1983; Smulders, Kok, Kenemans, & Bashore, 1995). A matter of interest was the extent to which the specific pattern of results obtained by Ford et al. (1979) would hold if their manipulation of memory search were replaced by stimulus degradation. Variations in stimulus deg-

[2]If there really exists an age- and memory load-related bias in the latency of P300 that "pushes" a true overadditive interaction between these factors into an artificial additive effect, it is expected that the same bias may lead to an underadditive interaction if it is even stronger. Such an underadditive interaction between age and memory set size has indeed been observed by Ford, Pfefferbaum, Tinklenberg, and Kopell (1982), in a follow-up study of Ford et al. (1979). If this underadditive interaction were not produced by the proposed bias, the interaction could be explained only by the improbable assumption that memory scanning is faster in the elderly than in the young! Furthermore, Looren de Jong, Kok, and van Rooy (1988) even found a *decrease* in P300 latency in conditions with a higher memory load. They also explained this unexpected effect as the result of P300 being overlapped by an increasing negative wave in conditions with a higher memory load.

radation were not expected to be associated with the confounding effects of the large negative wave observed in memory search tasks. S-R compatibility was varied to affect response selection processes (Sanders, 1980). In contrast to stimulus degradation, variations in S-R compatibility were expected to have little or no effect on P300 latency (Magliero et al., 1984; McCarthy & Donchin, 1981, 1983). If the effect of aging on P300 latency is additive, the effect should be constant across the levels of stimulus degradation for both compatible and incompatible responses. In contrast, if the effect of age contains a multiplicative component, the age-related slowing of P300 should be increased when the stimulus is degraded.

These hypotheses can be rephrased in the terminology of the additive factor method. Recall that this method indicates that additive factor effects suggest the engagement of different stages of processing, whereas interactive factor effects suggest that a common stage of processing was engaged (Sternberg, 1969). In the present study, these effects lead to the following set of predictions. First, if aging affects both the stages of stimulus encoding and response selection, then effects of age on RT should interact with the effect of stimulus degradation and S-R compatibility. Second, if the interaction between age and stimulus degradation on RT reflects a genuine effect on encoding processes preceding the determination of P300 latency, rather than an effect on response-processes following P300 (labeled "confidence" by Ford et al., 1979), then the same type of interaction should be obtained for P300 latency. In contrast, independent of the influence of age on RT, effects of age on P300 latency should not interact with S-R compatibility, because P300 latency should not be sensitive to variations in S-R compatibility. Finally, because stimulus degradation and S-R compatibility have been combined factorially in two age groups, the robustness of the stage model to the effects of aging can be tested. Stage robustness is obtained if the relation between two factors (in this case, stimulus degradation and S-R compatibility) does not change when a third factor (in this case, age group) is added to the factor array (Sanders, 1980; Sternberg, 1969). For example, the additivity between stimulus degradation and S-R compatibility has been shown to be independent of the effects of sleep loss (Sanders, Wijnen, & Van Arkel, 1982) and presentation mixture (mix vs. blocked presentation of levels of a factor; Van Duren & Sanders, 1988). If this additive relation is not apparent among the older subjects, then the possibility is raised that the processing architectures of the young and the elderly differ in a qualitative manner, and that the effect of age on RT may not be explained fully by a mere difference in processing speed.

Methods

Subjects

Thirteen young men (mean age 21.5 years, range 19–26 years), students at the University of Amsterdam, and 15 elderly men (mean age 69.8 years, range 65–77 years) served as subjects.[3] Young subjects received course credits and the elderly received Hfl. 25 for their participation. All subjects were right-handed and had normal or corrected-to-normal vision. To enable reliable comparisons between RT and ERP data, the data of one young and four elderly subjects with no discernible P300 component in the average waveforms were left out of the analyses. Thus, the analyses were done on the data from 12 young (mean age 21.3 years, range 19–26 years) and 11 elderly (mean age 70.9 years, range 65–77 years) subjects. An extended medical questionnaire revealed that all subjects were in good health, no subject had a history of neurological disorder, and three elderly subjects were under medication for minor heart disorders. All but two elderly subjects had at least secondary education. After the choice-RT tasks, all subjects performed a selective attention task (reported in Kenemans, Smulders, & Kok, 1995).

Stimuli

Stimuli were the words "LINK" and "RECH" (abbreviations of the Dutch words for "left" and "right," respectively), presented in the center of a video monitor (Zenith VGA). Each letter of the stimulus consisted of dots (6×6 pixels, black-on-white, 2-pixel spacing). Each word was surrounded by a rectangular frame consisting of identical dots. Each letter was seven dots (19 mm) high and five dots (14 mm) wide; the frame was 35 mm high and 83 mm wide. The stimulus words were degraded by removing eight dots from the frame and placing them in the field around each letter. To prevent subjects from using specific cues, there were four versions of each degraded word; that is, in both words four different noise patterns were superimposed over each letter such that all letters were degraded by each noise pattern once, provided that the dots of the noise pattern did not coincide with dots forming that letter.

Task and Design

Subjects sat alone in a dimly lit room at a distance of 160 cm from the monitor on which the stimuli were presented at eye level. Presentation time was 1,000 ms and the interval between the onsets of two consecutive stimuli varied between 2,590 and 3,090 ms following a uniform random distribution. A central fixation cross was presented during the entire interstimulus interval. Four blocks of trials were presented (intact/compatible, degraded/compatible, intact/incompatible, degraded/incompatible), each block containing 136 trials. In compatible blocks, subjects were instructed to respond to a stimulus by pressing a button with the index finger at the hand indicated by the meaning of the word (e.g., the word "LINK" [left] called for a left button press). In incompatible blocks, the mapping of word meaning to response finger was reversed (e.g., the word "LINK" called for a right button press). The response devices were attached to the ends of the left and right arms of the chair in which the subject was seated. The order of blocks was counterbalanced across subjects. Before each block, subjects were informed of its nature. Subjects were instructed to respond fast and accurately. Preceding data acquisition, subjects completed a practice session in which each type of block was repeated until the subject's error rate was below 10%. The average amount of practice in intact/compatible, degraded/compatible, intact/incompatible, and degraded/incompatible conditions was 48, 65, 48, and 92 trials, respectively for the young, and 48, 52, 68, and 48 trials, respectively for the elderly.

Physiological Recording

The electroencephalogram (EEG) was recorded at Fz, Cz, Pz, and Oz (Jasper, 1958) by means of tin electrodes attached to an electro-

[3]Originally, 20 elderly subjects were invited to come to the laboratory. However, the experiment contained an extra condition with stimuli that were degraded to such an extent that they could not be discriminated by 11 elderly and 1 young subject, even after extended practice. Of these elderly, the first 5 were sent home after the practice series, so that no experimental data are available. After this result, we relaxed our criteria for the inclusion of subjects. It was sufficient if a subject only met the criteria set for reasonable performance (no more than 10% errors) in the conditions involving intact and normally degraded stimuli. As a result, no more subjects had to be excluded. The incomplete data of the conditions involving the heavily degraded stimuli were discarded from further analyses.

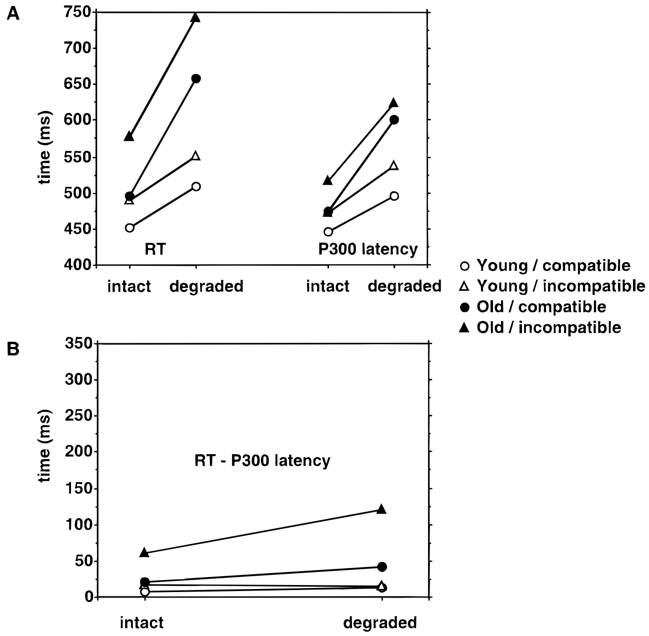

Figure 1. The effects of stimulus degradation (Int., Deg.) and stimulus–response compatibility (Compatible, Incompatible) on reaction time, P300 latency, and RT − P300 latency for young and old subjects.

cap. Linked earlobes served as the reference. The vertical components of the electrooculogram (EOG) were recorded bipolarly from sites above and below the pupil of the right eye, and the horizontal components were recorded bipolarly at the outer canthus of each eye. A ground electrode was placed on the forehead. Electrode impedance was kept below 8 kΩ. Amplifiers were set to a time constant of 5 s and a high frequency cut-off of 35 Hz. The 100-Hz sampling started at 490 ms before stimulus onset and lasted for 2,560 ms, generating series of 256 time points.

Data Reduction

Trials on which an error was made (3.4% of trials, on average) and trials on which RT differed from the mean by more than 2.5 standard deviations (SD; 2.4%) were excluded from analysis. In addition, trials with artifacts (saturation of the AD-converter or an EEG amplitude of more than 100 μV, 5.8%) were excluded. Ocular artifact in the EEG was controlled by regression analysis in the frequency domain (Woestenburg, Verbaten, & Slangen, 1983). For each subject and experimental condition the ERPs were low-pass filtered (−3 dB at 3.4 Hz; Ruchkin & Glaser, 1978; Smulders, Kenemans, & Kok, 1994).

P300 latency was estimated at the single trial level using the vector filter procedure (Gratton, Coles, & Donchin, 1989; Gratton, Kramer, Coles, & Donchin, 1989). For each trial, the waveforms from the four scalp electrodes were summed using differential weights to yield a composite waveform that optimizes the discrimination between P300 and other overlapping components and noise. The used weights were 0.1611, −0.5335, 0.8210, and 0.0, for Fz, Cz, Pz, and Oz, respectively (Fabiani, Gratton, Karis, & Donchin, 1987). The latency of the largest positive peak in the vector filter output in a window extending from 300 to 1,000 ms served as P300 latency. To test effects on the time interval between the P300 and the overt response, RT and P300 latency were contrasted as a within-subjects factor (i.e., RT − P300 latency was computed) in a separate analysis of variance (ANOVA; cf. Ford et al., 1979). All reported F values were significant at the .05 level with df (1,21), unless stated otherwise.

Results

Reaction Time

The effects on median RT are shown in the left panel of Figure 1A. RTs were longer in the elderly than in the young, longer to degraded than to intact stimuli, and longer when the S-R mapping was incompatible than when the S-R mapping was compatible, significant main effects: Age, $F = 48.0$; Stimulus Degradation, $F = 100.6$; S-R Compatibility, $F = 25.2$. The effects of stimulus degradation and S-R compatibility did not interact, $F = 0.1$. The effect of age on RT was larger for degraded than for intact stimuli, Age × Stimulus Degradation, $F = 22.2$. The effect of age tended to be larger for incompatible than for compatible S-R mappings, Age × S-R Compatibility, $F = 3.0$, $p = .10$. We suspected that the weakness of this effect was related to our relatively small subject sample sizes. Indeed, for this latter comparison, the effect of age became significant when the excluded subjects were included in the analysis of the RT data, Age × S-R Compatibility, $F(1,26) = 4.87$, $p < .05$. For mean RT, the pattern of results was the same. In sum, all variables affected RT; the effects of the two task variables were additive, and effects of age interacted positively with the effects of both task variables.

Errors

Table 1 lists the error rates. Error rates were higher when stimuli were degraded rather than intact and also higher when the S-R mapping was incompatible than when it was compatible, significant main effects: Stimulus Degradation, $F = 20.4$; S-R Compatibility, $F = 9.3$. The effect of stimulus degradation was larger among the elderly than among the young, Age × Stimulus Degradation, $F = 5.9$.

P300 Latency

The grand average ERP waveforms are shown in Figure 2. The right panel of Figure 1A shows the effects of age and the task variables on the median P300 latency. P300 latency was longer in the elderly than in the young, longer with degraded than intact stimuli, and longer when the S-R mapping was incompatible than

Table 1. *Mean Percentage of Errors as a Function of Stimulus Degradation and Stimulus–Response Compatibility in Young and Old Subjects*

	Compatible	Incompatible	Difference
Young			
Intact	1.6	3.3	1.7
Degraded	2.5	4.0	1.5
Difference	0.9	0.7	−0.2
Old			
Intact	1.0	3.3	2.3
Degraded	4.0	5.9	1.9
Difference	3	2.6	−0.4
Age effect			
Intact	−0.6	0	
Degraded	1.5	1.9	

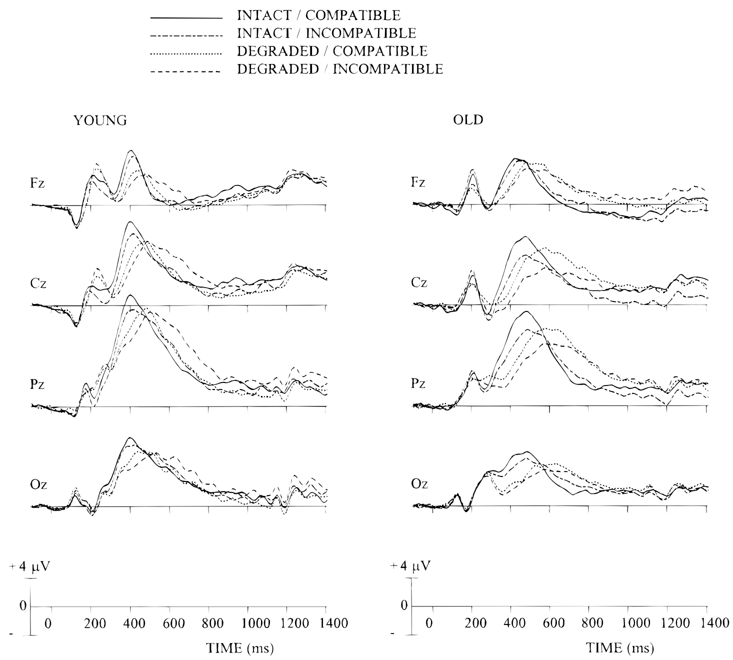

Figure 2. Grand average event-related potentials recorded at Fz, Cz, Pz, and Oz as a function of stimulus degradation (Intact, Degraded) and stimulus–response compatibility (Compatible, Incompatible) for young and old subjects.

when it was compatible, main effects: Age, $F = 19.8$; Stimulus Degradation, $F = 150.9$; S-R Compatibility, $F = 40.1$. The effect of age on P300 latency was larger for degraded than for intact stimuli, Age $\times$ Stimulus Degradation, $F = 17.9$. No other interaction effects on P300 latency approached significance, all $F < 1$, except Age $\times$ Stimulus Degradation $\times$ S-R Compatibility: $F = 2.5$, $p = .13$.[4]

RT – P300 Latency

Figure 1B shows the effects of aging and task variables on the time interval between P300 latency and the overt response. This time interval was lengthened when the S-R mapping was incompatible rather than compatible, significant main effect: S-R Compatibility, $F = 8.4$; it tended to be longer for degraded than for intact stimuli, Stimulus Degradation, $F = 3.9$, $.05 < p < .10$, and it also tended to be longer in the elderly than in the young, Age, $F = 3.7$, $.05 < p < .10$. The effect of age on this interval tended to be larger when the stimuli were degraded than when the stimuli were intact, Age $\times$ Stimulus Degradation, $F = 3.1$, $.05 < p < .10$. The effect of age on this interval was significantly larger when the S-R mapping was incompatible than when the mapping was compatible, Age $\times$ S-R Compatibility, $F = 5.6$.

Summary of ERP Results

In sum, all variables affected the time interval between the moment of the stimulus and P300; the effects of the two task variables were additive, and the effects of age interacted only with the effects of stimulus degradation. The effects on the interval between P300 and the response were mostly weak or absent. This interval was lengthened significantly only by S-R incompatibility, an effect that was larger in the elderly than in the young. The latter result is logically consistent with the presence of an overadditive interaction between Age and S-R compatibility on RT and the absence of an interaction on P300 latency, as was observed.

[4]Note that these effects resulted from single-trial analyses using the vector filter procedure. To maximize comparability between the present results and those of Ford et al. (1979), additional ANOVAs were carried out using each subjects' P300 latency at Pz in the average ERP as the dependent variable (cf. also Discussion section). The results were highly similar to the results of the single-trial analysis, ruling out explanations of differences between results of the two studies in terms of differences in scoring methods.

Discussion

The effects of age on RT were enlarged invariably in more difficult task conditions, whether the task was made more difficult by visually degrading the stimuli or by setting an incompatible S-R mapping. For the latency of the P300, the pattern of results was different. The effects of age on P300 latency were enlarged as the stimuli were degraded, but if the S-R mapping was set to be incompatible the effects of age on P300 latency did not change. Both task manipulations had an effect on the latency of the P300.

Despite our relatively small subject sample sizes, the present RT results are in accordance with the conclusions based on the regression analyses initiated by Brinley (1965), and continued by Cerella and co-workers (Cerella, 1985; Cerella et al., 1980), Salthouse and Somberg (1982), Bashore et al. (1989), and others. Like these studies, the present results indicated that a multiplicative factor contributed to the effects of age on RT, independently of the task manipulation. The P300 results, however, can be explained neither by a purely multiplicative nor by a purely additive component alone. Whereas a multiplicative component was involved in the age-related delay in processing a degraded stimulus, the age-related delay in making an incompatible response included only an additive component. Apparently, for P300 latency, the contribution of a multiplicative component depends on the task variable.

Ford et al. (1979) did not find a multiplicative component for effects of age on the latency of P300 in a memory search task. Instead, effects of age on P300 latency were additive with an increasing load of memory search processes, an effect that has been replicated by others (Pratt, Michalewski, Patterson, & Starr, 1989; Strayer, Wickens, & Braune, 1987). In contrast, in our study the effects of age on P300 latency increased when the stimulus was degraded, indicating the presence of a multiplicative component. Although both memory load and stimulus degradation had sizable effects on P300 latency, again the task content determined whether a multiplicative or additive component best described the age-related delays in P300. Our results can be modeled together with the pattern of results commonly observed in memory search tasks in two simple ways.

First, the process of stimulus encoding is possibly truly affected in the elderly, whereas the process of memory scanning is not. From this perspective, the impairment in memory scanning that is apparent in the RT effects may be due to a decreased response-confidence in more difficult task conditions, as suggested by Ford et al. (1979). In the present results, the increase in effects of age with degraded versus intact stimuli tended to be smaller for P300 latency than for RT. This observation was suggested by the weak interaction between age and degradation for RT-P300 latency. Possibly, in addition to a true delay in encoding processes in the elderly, the increase in RT in the more difficult stimulus-degraded conditions was due in part to a decrease in response-confidence.

The second possibility is that both stimulus encoding and memory scanning processes are affected by age. From this perspective, the increased effect of age on P300 latency in the higher memory load conditions is masked by the overlap of increasing "search" negativity, as argued in the introduction. Okita and co-workers proposed that the search negativity is related to conscious effortful processing involved in the memory scanning process when the items in the memory set change regularly (Okita et al., 1985; Shiffrin & Schneider, 1977). It is conspicuous that the task variable in our experiment that is related to conscious, effortful response selection (Sanders, 1983) yielded a pattern of results that was comparable to the typical pattern in the memory-scanning task: S-R incompatibility by itself increased P300 latency, but this increase did not vary with age.

The latter result, in particular, prompted the question whether our P300 results were biased by a negative wave overlapping P300 that was similar to the search negativity commonly observed in memory scanning tasks. An additional post hoc analysis was carried out to explore this possibility. The rationale was that if our pattern of results were influenced by biases related to overlap with a frontocentral negativity, similar to the search negativity, these biases should be stronger at Cz and Fz than at Pz. We determined the latency of the largest peak between 300 and 1,000 ms in the average ERP at Fz, Cz, and Pz, and carried out additional ANOVAs for each location (data of two young subjects were not used because they lacked an identifiable P300-like component at Fz or Cz). At Pz, the results were highly similar to the results of the single-trial analysis presented above. One relevant question was whether the interaction between effects of age and stimulus degradation would be augmented at more frontal locations than Pz. In fact, the opposite was true: at Cz and Fz, there was no significant interaction between effects of age and stimulus degradation, both $F < 1$. The other important result was the additivity of effects of age and S-R compatibility. If this additivity turned into a negative interaction at Cz or Fz, we would presume that an overlapping negativity had been effective, and that the same negativity might have biased the estimate of P300 at Pz, turning a true positive interaction into the additive effect that we observed. The additional ANOVAs, however, revealed no negative interaction between age and S-R compatibility at either Cz or Fz, both $F < 1$. In conclusion, there is no evidence that our two most relevant P300 latency results were the product of a bias associated with an overlapping negative wave with a frontocentral maximum.

It is informative to use the additive factor method as a heuristic for interpreting the present results. Stimulus degradation and S-R compatibility had additive effects on RT. This additivity allows for the postulation of a two-stage model of information processing in these tasks (Figure 3A). The additivity held not only for the young but also for the elderly, indicating that this model is robust for the effects of aging. The effects of degradation were augmented in the elderly. The effects of S-R compatibility were practically doubled in the elderly, although the interaction was statistically weak. The two-stage model in which age affects both stages (see Figure 3A) can explain these results effectively. Next, it will be shown that this simple model must be extended to the model in Figure 3B if it is to explain the effects on the latency of the P300.

Both stimulus degradation and S-R compatibility affected the latency of the P300 in an additive manner, supporting the two-stage model derived from the RT results. The effect of stimulus degradation was expected, but the substantial effect of S-R compatibility was not. McCarthy and Donchin (1981) and Magliero et al. (1984) did not find a significant effect of S-R compatibility on the latency of the P300. A critical difference between these experiments and ours may be that we varied S-R compatibility between, rather than within blocks of trials. Therefore, our P300 latency results were more vulnerable to "nonspecific" block effects, e.g., differential preparation for compatible and incompatible trials. Consistent with this inference, other researchers have found that semantic S-R compatibility, when varied between blocks, affects P300 latency (Pfefferbaum, Christensen, Ford, & Kopell, 1986). We also found that, for P300 latency, stimulus degradation interacted with age, supporting the RT evidence for an effect of age on encoding. In contrast, for P300 latency, S-R compatibility was additive with age. In view of the interaction between S-R compatibility and age on RT, this finding cannot be explained by the simple two-stage model in which a single stage affected by S-R compatibility precedes the moment at which P300 latency is determined. To accommodate both P300 and RT results, the two-stage model must be modified to include an extra stage, as depicted

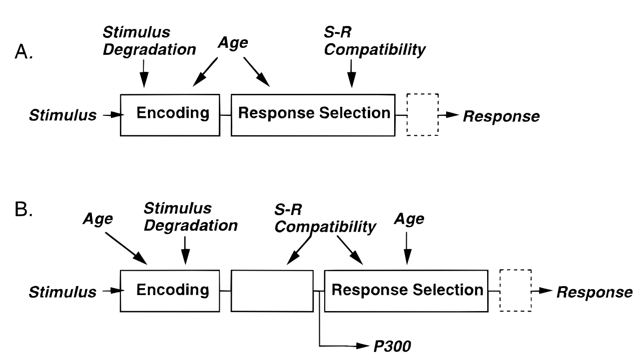

Figure 3. The simplest stage models that produce the obtained pattern of effects of stimulus quality and stimulus–response compatibility in young and old adults. Whereas (A) takes into account reaction time results only, (B) takes into account both reaction times and the latencies of the P300.

in Figure 3B. In this model, two stages precede the moment at which P300 latency is determined; the first is affected by both degradation and age (leading to Age × Stimulus Degradation interactions for both P300 latency and RT) and a second stage is affected uniquely by S-R compatibility (leading to a main effect of S-R compatibility for P300 latency). After the moment at which P300 latency is determined, a third stage is affected by both S-R compatibility and age (leading to the Age × S-R compatibility interaction for RT, but not P300 latency). Although three stages are obviously needed here, how the two stages affected by S-R compatibility should be labeled is less obvious. First, in accordance with McCarthy and Donchin (1981, 1983), the third stage may be labeled "response selection." The second stage would then consist of processes affected by S-R compatibility, but not by aging (e.g., a nonspecific "block" effect, see above). Second, analogous to the reasoning of Ford et al. (1979), the third stage could consist of processes sensitive to a "lowered confidence" in more difficult (S-R-incompatible) conditions. The second stage would then be labeled "response selection," which is not affected by age. We consider the first labeling pattern the more parsimonious, as it is in accordance with the widely held view that P300 is normally not affected by response selection processes. Furthermore, the first labeling pattern preserves the RT-interpretation, namely that age affects response selection.

In conclusion, effects of age on the latency of the P300 can be augmented in task conditions that, by themselves, lead to a delay in P300. This conclusion contrasts with the results of Bashore et al. (1989) and, to a lesser extent, with the results from studies of memory scanning in the elderly (e.g., Ford et al., 1979). From the fact that the critical task condition involved degraded versus intact stimuli it follows that at least part of the well-documented delay in P300 in the elderly (estimated at 1.3–1.5 ms/year, see Polich, 1991, for a review) is probably due to a delay in stimulus encoding processes. This conclusion is given additional support by studies in which stimulus encoding processes are excluded. When a subject has to respond to an occasional omission in an ongoing train of stimuli, a P300 occurs (Sutton, Tueting, Zubin, & John, 1967). The latency of this "emitted" P300 is equivalent for the young and the elderly (Michalewski, Patterson, Bowman, Litzelman, & Thompson, 1982). In sum, at least a part of the effect of age on the latency of the P300 is due to a delay (in stimulus encoding) that is directly responsible for a slower overt reaction. This conclusion augments the utility of P300 latency as an index of the functional integrity of the central nervous system in elderly subjects, because it reduces the chance that the delay in P300 in the elderly is only an epiphenomenon. At the same time, effects of age on the latency of the P300 were not augmented in another task condition (incompatible S-R mapping) that, by itself, also led to a delay in P300. Apparently, the size of age effects on P300 latency depends heavily on the specific task content. If effects on P300 latency can be isolated from effects of overlapping negative waves, more research can help to unravel the role of response-confidence, or stimulus-reevaluation processes in the dissociation between effects of age on the timing of P300 and the overt response.

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