Published in final edited form as:

Neuropsychol Dev Cogn B Aging Neuropsychol Cogn. 2014 ; 21(6): 633–673. doi:
10.1080/13825585.2013.850058.

Response-specific slowing in older age revealed through differential stimulus and response effects on P300 latency and reaction time

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Abstract

Older age produces numerous changes in cognitive processes, including slowing in the rate of mental processing speed. There has been controversy over the past three decades about whether this slowing is generalized or process-specific. A growing literature indicates that it is process-specific and suggests it is most dramatic at the interface where a stimulus input is translated into a response output. We tested this hypothesis using a task in which young and older adult males made either compatible or incompatible responses to the word LEFT or RIGHT shown briefly and variously located in a 4 row $\times$ 6 column matrix surrounded by # signs or by letters chosen randomly from the sets A-G or A-Z. Processing speed was measured using P300 latency and reaction time. Experimental effects on these two measures provided support for the hypothesis in revealing that stimulus identification processes were preserved, whereas processes related to translating a stimulus input into a designated response output and then selecting that response were compromised in the elderly.

Keywords

General slowing; Process-specific slowing; S-R translation; P300 latency; Reaction time

Research to characterize the effects of older age on mental processing speed can be traced to Birren's (1965) *complexity hypothesis*: slowing in older adults reflects a growing interdependence between central stimulus and response output processing as task demands increase that is proportionately equivalent across all components of processing and all levels of task difficulty (Birren, Woods, & Williams, 1980). Impressive early support for this *general slowing* hypothesis was provided in the consistent finding that regression of the

reaction times (RTs) of older adults on those of young adults, an approach inspired by Brinley (1965), yielded a linear function with a slope greater than 1.0 and a near-zero intercept for data taken either from experimental conditions within a single study or from a wide range of tasks of varying difficulty across a large number of different studies (e.g., Cerella, 1985; Cerella, Poon, & Williams, 1980; Hale, Lima, & Myerson, 1991; Lima, Hale, & Myerson, 1991; Myerson & Hale, 1993; Salthouse, 1985a, 1985b; Verhaeghen & Cerella, 2008). However, contemporaneous work yielded equally impressive support for the alternative *process-specific* hypothesis that assumes older age induces varied patterns of change across speeded decision-making tasks in which some elements of processing are spared while others are slowed to differing degrees (e.g., Bashore, Osman, & Heffley, 1989; Bashore, Ridderinkhof, & van der Molen, 1998; Bashore & Smulders, 1995; Fisher, Duffy, & Katsikopoulos, 2000; Fisher, Fisk, & Duffy, 1995; Fisk & Fisher, 1994; Perfect, 1994; see discussions of the theoretical debate in Perfect & Maylor, 2000).

Compelling support for process-specific slowing is found in RT studies that have identified patterns of effects that cannot be explained by general slowing in focused visual attention and search (e.g., Madden & Langley, 2003; Madden, Pierce, & Allen, 1996; Madden et al., 2002), semantic priming and lexical decision-making (e.g., Burke, White, & Diaz, 1987; Madden, 1992; Madden, Pierce, & Allen, 1993), counting (e.g., Basak & Verhaeghen, 2003; Geary & Wiley, 1991; Sliwinski, 1997), mental arithmetic (e.g., Allen, Ashcraft, & Weber, 1992), and perceptual load (e.g., Madden & Langley, 2003; Maylor & Lavie, 1998). Similarly, observations that some elements of speeded attentional processing may not decline later in life call into question the view that age induces task-indiscriminant generalized slowing (e.g., Besic, Kramer, & Boot, 2007; Bucur, Allen, Sanders, Ruthruff, & Murphy, 2005; Whiting, Madden, & Babcock, 2007). Moreover, a cogent challenge to the analytical bedrock of the general slowing hypothesis by Ratcliff, Spieler, and McKoon (2000) revealed in a series of simulations that random or systematic age-related variations in one or more processing components, irrespective of their nature, yielded regression functions like those used to support the hypothesis, thereby providing "...only weak constraints on modeling" (p. 18).

This research indicates that the issue today is isolating the components of speeded decision-making that are vulnerable to older age, determining the relative magnitudes of their slowing, and characterizing the extent to which they slow across different cognitive tasks. Indeed, important advances have been made in RT studies addressing this issue. Results from numerous studies suggest that the most pronounced effects of older age on dual-task processing (Allen, Smith, Vires-Collins, & Sperry, 1998; Hartley, 2001; Hartley & Little, 1999), picture-drawing and word writing (Amrhein & Theois, 1993), simple signal detection (Ratcliff, Thapar, & McKoon, 2001), inhibition of return (Hartley & Kieley, 1995), spatial stimulus-response (S-R) conflict monitoring (e.g., Castel, Balota, Hutchison, Logan, & Yap, 2007; Kubo-Kawai & Kawai, 2010; Proctor, Pick, Vu, & Anderson, 2005; Vu & Proctor, 2008), letter identification (Thapar, Ratcliff, & McKoon, 2003), and lexical decision (e.g., Allen, Lien, Murphy, Sanders, Judge, & McCann, 2002; Allen, Smith, Groth, Pickle, Grabbe, & Madden, 2002) occur early and/or late in processing, with the intermediate elements of processing being relatively spared. Among the most compelling findings are

those generated in a series of studies by Hartley and colleagues that point to response selection as being most vulnerable to older age (Hartley, 1993, 2001; Hartley & Kieley, 1995; Hartley & Little, 1999; Hartley & Maquestiaux, 2007; Hartley, Kieley, & Slabach, 1990; also see Rubichi, Neri, & Nicoletti, 1999; Spieler, Balota, & Faust, 1996).

Next, we review results from cognitive psychophysiological studies, those in which RT and event-related (ERP) and movement-related (MRP) brain potential component latencies are measured,¹ that converge with those from RT studies to support the conclusion that differential slowing occurs both early in stimulus processing and later in response processing, with the most dramatic effects of age-related slowing being expressed at the response end. Of particular interest is that age effects on component latencies differ from or conform to those on RT (i.e., are dissociated or associated) in ways that sharpen conclusions drawn from behavioral studies.

Cognitive psychophysiological studies

Ford, Roth, Mohs, Hopkins, and Kopell (1979) first reported that increases in RT produced by increases in the number of stimuli (digits 0–9) held in memory in a Sternberg (1969) memory scanning task were about twice as large among older than young adults, but increases in P300 latency, thought to index stimulus processing time (e.g., Kutas, McCarthy, & Donchin, 1977) and known to increase systematically from adolescence to late adulthood (e.g., Goodin, Squires, Henderson, & Starr, 1978), were nearly identical in the two age groups (i.e., there was a dissociation of age effects on the two measures). The patterns they found suggested that age-related slowing occurred during early stimulus encoding and late response selection and execution, not during intervening stimulus-by-stimulus memory scanning and comparison (also see Ford, Pfefferbaum, Tinklenberg, & Kopell, 1982; Strayer, Wickens, & Braune, 1987).

A meta-analysis by Bashore et al. (1989) yielded a similar dissociation of age effects on RT and P300 latency. They found a regression function for RT with a slope exceeding 1.0 and a near-zero intercept that resembled the prototype offered in support of generalized central slowing, but a function for P300 latency with a slope of 1.0 and an elevated intercept that,

¹In addition to components like the P300 that have been associated primarily with stimulus processing, there are components that have been distinguished as indices of response processing. The most prominent of these components is the lateralized readiness potential (LRP). This component, identified independently by Gratton, Coles, Sirevaag, Eriksen, and Donchin (1988) and DeJong, Wierda, Mulder, and Mulder (1988), reflects response system activation. Its temporal and morphological properties provide indices of response system activation that originates from pre- and primary motor cortex (Coles, 1989; Leuthold & Jentzsch, 2002; Requin & Riehle, 1995). Since its discovery, the sensitivity of the LRP to variations in this activation has been documented quite consistently (e.g., Band & Miller, 1997; DeJong, Liang, & Lauber, 1994; Eimer, 1998; Hackley & Miller, 1995; Masaki, Wild-Wall, Sangals, & Sommer, 2004; Miller, Coles, & Chakraborty, 1996; Osman, Bashore, Coles, Donchin, & Meyer, 1992; Osman, Moore, & Ulrich, 1995; Ridderinkhof, van der Molen, Band, & Bashore, 1997; Sangals, Sommer, & Leuthold, 2002). Osman and Moore (1993) refined the sensitivity of the LRP by deriving the stimulus- (measured from stimulus onset) and response- (measured back from the overt response) locked LRP, or sLRP and rLRP, respectively, to infer the relative influences of stimulus and response processes on the timing of response system activation. These measures can be used to advantage in assessing the differential influence of advancing age on neurocognitive processing speed (an early example of which is in Zeef & Kok, 1993).

The rLRP is thought to index response processes that are independent of stimulus processing, whereas the sLRP is considered to reflect those aspects of stimulus processing that influence response activation. Indeed, these two variants of the LRP permit input-output processing to be partitioned into premotor (all stimulus processing through response selection, indexed by the onset of the sLRP) and motor (all processing associated with initiating the response output command and executing the motor response, indexed by the onset of the rLRP) times (Masaki et al., 2004; Possamai, Burle, Osman, & Hasbroucq, 2002). Moreover, the offset time of the sLRP can be used to infer inactivation of a specific response channel. An early example of how changes in the onset and offset of the sLRP can guide inferences about the temporal dynamics of cognitive processing is found in Osman et al. (1992).

according to the logic of proponents of generalized slowing, reflected changes in peripheral processing speed.² However, since it was well known that the P300 was generated from central, albeit unspecified, sources the function for P300 latency could not be explained by the assumptions underlying the RT analyses. More broadly, the differences in the two regression functions challenged the logical foundation on which these analyses rested. They suggested, as did the findings from Ford et al., that some central processes may be slowed (e.g., stimulus encoding), some may be spared (e.g., stimulus identification), and some may be particularly susceptible to decline (e.g., response selection) later in life.

That differential decline and sparing may occur among older adults is suggested further in patterns of dissociations and associations of age effects on RT and several cognitive psychophysiological measures reported by numerous investigators (e.g., Band & Kok, 2000; Falkenstein, Yordanova, & Kolev, 2006; Fjell, Rosquist, & Walhovd, 2009; Kolev, Falkenstein, & Yordanova, 2006; Smulders, Kenemans, Schmidt, & Kok, 1999; van der Lubbe & Verleger, 2002; Wild-Wall, Falkenstein, & Hohnsbein, 2008; Yordanova, Kolev, Hohnsbein, & Falkenstein, 2004; Zeef & Kok, 1993; Zeef, Sonke, Kok, Buiten, & Kenemans, 1996). Although these studies generally reveal declines in early stimulus processing among older adults, they point most suggestively to a variegated pattern of influences of older age on late response processing that may differ with the type of stimulus-response output processing demand. In early work, Zeef and Kok (1993, task 1) and Zeef et al. (1996) reported larger increases in RT and MRP measures of central and peripheral response system activation speed among older than young adults in conjunction with comparable increases in P300 latency among the two groups when, in an Eriksen flanker task (Eriksen & Eriksen, 1974), they identified and responded to a target stimulus flanked by stimuli signaling the opposite response (i.e., those producing flanker interference). However, Smulders et al. (1999) observed larger increases in both RT and P300 latency among older than young adults when single targets (abbreviations of the Dutch words for “left” and “right” presented at visual fixation) signaling left or right button presses were degraded. The pattern of dissociation and association found in these two studies suggests that intermediate elements of stimulus processing are preserved, but that early stimulus encoding and later response selection processes are compromised among the elderly.

The conclusions drawn by Zeef and Kok (1993, task 1) and Zeef et al. (1996) were based, however, on findings from tasks in which S-R conflict was not varied directly. In contrast, both Smulders et al. (1999) and Zeef and Kok (1993, task 2) varied S-R conflict directly. Smulders et al. manipulated symbolic S-R mappings, subjects made compatible or incompatible responses to the abbreviated Dutch words for “left” and “right”. They found

²Two functions were derived for P300 latency, both of which differed from that for RT. Included in one analysis were all of the tasks in which P300 latency was measured, some portion of which did not require an overt response, whereas in the second analysis the only tasks included were those in which P300 latency was measured in conjunction with an overt response (i.e., RT data were also collected). Linear regression functions were derived in both cases (r^2 s of .91) with slopes approximating 1.0 (0.95, 0.93) and intercepts elevated significantly above zero (80.10 ms, 89.99 ms). Note that a P300 can be elicited under conditions in which the subject is not required to make any overt response. All that is required is that a stimulus or class of stimuli be designated as a target calling for some type of covert response (e.g., keep a running mental count of its occurrence). A P300 will be elicited whenever this task-relevant stimulus is presented, the subject recognizes its occurrence, and updates the running mental count. Indeed, in the paradigmatic variant of the classic task for eliciting the P300, the oddball task, the subject's responsibility is to keep a silent running mental count of each occurrence of the designated target and to refrain from counting occurrences of the designated non-target. No overt response is required of the subject.

comparable increases in P300 latency in the two age groups along with larger increases in RT among older than young adults when incompatible as opposed to compatible responses were made. Zeef and Kok varied spatial S-R correspondence, subjects made left or right responses to a target letter, H or S, shown to the immediate left or right of visual fixation in a 5-letter horizontal array. Unlike Smulders et al., they found that the increases in both RT and P300 latency to spatially non-corresponding as opposed to corresponding targets (e.g., H signaling a left button press shown to the right as opposed to the left of visual fixation) were comparable in the two age groups. Thus, response selection speed may decline among the elderly when S-R conflict is symbolic, but not when it is spatial. However, subtle variations in task demands may alter age effects on spatial conflict resolution. van der Lubbe and Verleger (2002) found, for example, that the RT, but not the P300 latency, component of the Simon effect, slowing associated with spatial non-correspondence, was larger among older than young adults (for related RT findings see Kubo-Kawai & Kawai, 2010; Proctor et al., 2005; Simon & Pouraghabagher, 1978).

Evidence of both the vulnerability of the response end of processing to older age and the complexity of these effects is also found in work by Falkenstein and colleagues who assessed age-related slowing in simple, 2- and 4-choice RT, and Eriksen flanker tasks using ERP, MRP, and RT measures (Falkenstein et al., 2006; Kolev et al., 2006; Wild-Wall et al., 2008; Yordanova et al., 2004).³ Their work exposed a varied pattern of slowing among the elderly in the behavioral and electrophysiological measures supporting the following conclusions: (i) slowing early in stimulus processing accounts for a small proportion of the overall slowing seen among older adults; (ii) slowing at the level of response selection accounts for none of the overall age-related slowing in 2- and 4-choice reactions, whereas it accounts for some of it in the flanker task; and (iii) aging has as its primary effect slowing during activation and generation of a response output from motor cortex (for similar findings and conclusions in a motion onset perception study see Roggeveen, Prime, & West, 2007). In contrast, van der Lubbe and Verleger (2002) found factor effects on MRP activity consistent with a delayed onset of response selection processes, not with a prolonged duration of motor activation and generation processes.

The findings from the cognitive psychophysiological and RT studies we have reviewed point to early stimulus processing as being vulnerable to the slowing induced by older age, intermediate levels of stimulus processing as being less vulnerable and perhaps reasonably well-preserved, and later response processing as being most vulnerable to the effects of older age. The findings do not converge, however, on a particular level of response processing and in failing to do so underscore the complexity and task-dependence of age effects on mental processing speed (see reviews in Band, Ridderinkhof, & Segalowitz, 2002; Kok, 2000). This task-dependent complexity is revealed further in studies that failed to find dissociations of age effects on RT and P300 latency suggestive of differential slowing (e.g.,

³In Yordanova et al. (2004), Falkenstein et al. (2006), and Kolev et al. (2004) subjects completed auditory and visual variants of the four-choice reaction. Because our interest is in the visual modality, discussion is devoted to the effects reported in that modality. It should be noted, however, that the patterns of effects were very similar in the two modalities. It should also be noted that the subjects in Yordanova et al. completed a simple RT task in both modalities in addition to the four-choice reaction and in Falkenstein et al. a separate sample of young and older adults were run in a two-choice reaction. Of greatest interest to us are the results from the four-choice reaction so our discussion focuses on them.

Christensen, Ford, & Pfefferbaum, 1996; Pfefferbaum & Ford, 1988; Verleger, Neukäter, Kompf, & Vieregge, 1991).

The current study

Conceptual/methodological foundation

To explore further the extent to which response processes are more sensitive to advancing age than are intermediate stimulus processes we chose the McCarthy and Donchin (1981) matrix task, designed by them to exploit Sternberg's (1969) additive factors method (AFM) to test the hypothesis that P300 latency is influenced by the time required to identify an imperative stimulus, not by the time needed to select and execute a response to it. They varied the difficulty of identifying a target word ("LEFT" or "RIGHT") by embedding it in a matrix of # or letters selected randomly from the alphabet, the noise factor, and the difficulty of selecting a response (left or right button press) to the target by requiring a compatible or an incompatible response to it, the compatibility factor. Critical to this test were: (i) the two factors produce additive effects on RT thereby, according to AFM reasoning, supporting the conclusion that different stages of processing are influenced selectively and (ii) the effects of these two factors on P300 latency and RT are dissociated so that statistically-identified patterns of factor effects support the conclusions drawn about the processes thought to be reflected in these two measures.

Variations in these two factors did produce additive effects on RT; that is, the increase in RT for incompatible responses to targets surrounded by letters was the sum of the increase in RT associated with incompatible responses to targets surrounded by # (i.e., the cost of incompatibility) and compatible responses to targets surrounded by letters (i.e., the cost of noise). Thus, according to AFM reasoning, the two factors influence different processing stages (target identification and response selection). In contrast, the increase in P300 latency was large and highly significant when letters surrounded the target, but small and statistically insignificant when incompatible responses were made. McCarthy and Donchin argued that this pattern of dissociation indicates that P300 latency provides an index of target identification time that is independent of the time taken to select and execute the designated response. However, Magliero, Bashore, Coles, and Donchin (1984) found a similarly small cost of incompatibility on P300 latency that was statistically significant nonetheless. Thus, although small in size, P300 latency may be slowed in this task when response demands are increased.⁴ Controversy over the extent to which P300 latency is influenced by demands made on response processing emerged shortly after the McCarthy and Donchin publication and continues today. We summarize this controversy in the Discussion and, based on our results, speculate on the relative contributions of stimulus and response processes to changes in P300 latency.

⁴Both McCarthy and Donchin (1981) and Magliero et al. (1984) reported additive effects of noise and compatibility on RT. However, McCarthy and Donchin found a non-significant increase of 16 ms in P300 latency when incompatible responses were made, whereas Magliero et al. found a more complex pattern. They varied the target surround across 5 levels—no noise (#) and 4 letter surrounds (all As, A-D, A-G, and A-Z)—and blocked them within a test session (e.g., # vs. all As in one session; # vs. A-Z in another session, etc.). As in our experiment and in McCarthy and Donchin's, variations in S-R compatibility were mixed within blocks. In a separate analysis comparing data from the # and A-Z surrounds Magliero et al. found a non-significant increase of 12 ms in P300 latency when incompatible responses were made. However, an analysis encompassing every surround exposed "...a small (14 ms), but consistent, effect of S-R compatibility on P300 latency ...at all levels of noise" (p. 18).

Conceptual/methodological strengths of the matrix task

For reasons developed in that discussion, we assumed that P300 latency in this task reflects primarily the time needed to identify the target stimulus and substantially less, if any, the time required selecting a response to it. If so, AFM reasoning can be used to deepen our understanding of the differential effects of older age on stimulus and response processing speed. This reasoning provides a conceptual framework within which to interpret statistical patterns of factor effects; namely, experimental factors that influence different stages produce additive effects on mean RT, whereas factors that influence the same stage produce interactive effects. The major strength of this task is that target identification and response selection processes, as reflected in RT, can be isolated statistically as well as conceptually. The flanker and Simon tasks do not isolate these processes with equivalent statistical or conceptual precision.

In the flanker task distracting stimuli are usually response relevant, signaling either the target response or the alternative conflicting response. Hence, the onsets of stimulus and response activation processes are confounded, as was intended by Eriksen and Eriksen (1974). More precisely, the relative timing of target and flanker processing activation and the mutual influences of these activation processes as they emerge are not characterized with precision even though considerable progress has been made toward achieving that end (e.g., see Coles, Gratton, Bashore, Eriksen, & Donchin, 1985; Eriksen & Schultz, 1979; Gratton, Coles, Sirevaag, Eriksen, & Donchin, 1988; Magen & Cohen, 2007; Ridderinkhof, 2002; Ridderinkhof, van der Molen, & Bashore, 1995). Similarly, in the Simon task temporal activation of stimulus and response processes is confounded by the simultaneous delivery of stimulus information that is both relevant and irrelevant to task performance, a designated property of the target stimulus (e.g., its color) and its spatial location, respectively. To our knowledge, the precise relationship in this task between S-R correspondence (i.e., the *irrelevant* spatial location of the target vis-à-vis the spatial location of the designated response hand) and S-R compatibility (i.e., the *relevant* spatial location of the target vis-à-vis the spatial location of the designated response hand) has not been articulated experimentally or conceptually. Compelling arguments have been advanced nonetheless that the flanker interference and Simon effects are produced by response selection conflict between the flanker content and the response signaled by the target or the response associated with the spatial location of the target and the response it signals (e.g., see Hommel, 1993; Proctor & Vu, 2006; Simon, 1990; Treccani, Cubelli, Della Sala, & Umiltà, 2009).

In contrast, the distracting letters in the matrix task contain no response-relevant information, as intended by McCarthy and Donchin (1981). Rather, response conflict resolution is constrained to target stimulus processing. Moreover, a large literature spanning the last 4 or 5 decades converges on the conclusion that the cost of incompatibility is borne by processes that select the correct but incompatible response (e.g., see volume by Proctor & Vu, 2006). Thus, in the matrix task factor effects on target identification and response selection, as reflected in mean RT, are well differentiated, both statistically and conceptually. Consequently, it offers the possibility of dissecting the relative influences of

older age on stimulus and response processes in ways that complement the insights that have emerged from the flanker and Simon tasks.

Specific hypotheses and predictions under investigation

Our working hypothesis was that older age induces its most dramatic effects in this task at the response selection level, with processing at the target identification level being reasonably well preserved. A successful test of this hypothesis requires replication of the factor effects on RT in young adults reported in the earlier studies to demonstrate their consistency and, in so doing, reveal the effectiveness of this task in differentiating target identification from response selection processes. Justification would then be provided for using this task to extend AFM reasoning to interpreting differential influences of age on target identification and response selection processes as revealed, respectively, in P300 latency and RT.

Because it has been argued that any significant interaction between age and an experimental factor (e.g., S-R compatibility) thought to have a selective influence on a particular element of processing (e.g., response selection) may be an expression of generalized slowing in older age that is exponential rather than linear (e.g., Van Asselen & Ridderinkhof, 2001) and support for this argument has been provided in several regression meta-analyses (e.g., reviewed in Bashore & Smulders, 1995), analyses were done on mean values and natural logarithms.

In the analysis on mean values, we anticipated replicating the additive costs of noise and incompatibility on RT as well as the large cost of noise on P300 latency in young adults. However, given the inconsistent outcomes, we had no clear anticipation regarding whether or not a significant cost of incompatibility on P300 latency would emerge. With the addition of age as an experimental factor we expected the following interactions. (i) Larger costs of noise and incompatibility on RT among older adults (i.e., over-additive interactions between age and both noise and compatibility). (ii) Comparable costs of noise on P300 latency in young and older adults (i.e., an additive effect of age and noise). This dissociation in the influence of age on the effect of noise on RT and P300 latency supports the conclusion that age effects are response-related. (iii) If there is a cost of incompatibility on P300 latency, it will be larger in older than in young adults (i.e., an overadditive interaction between age and compatibility). With greatest confidence we anticipated a larger cost of incompatibility on RT among older adults and a dissociation of age effects on the cost of noise on RT and P300 latency revelatory of the selective influence of age on later response processes. We did not expect age to alter either the additive relationship between noise and S-R compatibility on RT or the relationship between these two factors on P300 latency (i.e., there would be no three-way interactions). The log natural (log N) analysis will expose differential slowing that exceeds general linear slowing. Accordingly, we expected the overadditive interaction on RT between age and noise to be eliminated and the overadditive interactions on RT and P300 latency between age and compatibility to remain.

METHODS

Subjects

Thirty-four (34) young men, ranging in age from 20 to 35 years old with a mean age of 27 years old, and 34 older men, ranging in age from 65 to 78 years old with a mean age 70 years old, completed this study. All candidates for the study underwent a two-phased screening process. In the first phase, their current and historical health status was assessed in a 90-question telephone interview. Candidates were excluded from the study who had a history of: (i) any type of medical disorder known to influence CNS functioning, (ii) any psychiatric disorder implicating the CNS (e.g., schizophrenia, bipolar disorder), (iii) alcoholism or other type of drug abuse, or (iv) prescribed use of centrally-acting medications (e.g., beta-blockers, anxiolytics). Approximately 50% and less than 5%, respectively, of the potential older and young adult pool were eliminated. Those not excluded completed the second screening phase in which they were given a medical examination that included history, full physical, vision test, auditory test, pulmonary function test, and exercise stress test. Candidates who had any medical illness identified in this examination that influenced CNS functioning or whose vision was less than 20/30 (corrected or uncorrected) were excluded from further participation in the study. Approximately 5% of the older, but none of the younger, candidates were excluded.

Each of the 68 candidates who passed the screening began the testing phase, 4 three-hour sessions, within 2 weeks of the medical examination and all of them finished it within a month. They were paid for their time, parking costs, and round-trip mileage. In the first session, for IQ matching purposes, subjects completed an abridged version of the Wechsler Adult Intelligence Scale (WAIS; Wechsler, 1955) developed by Satz and Mogul (1962) that has correlation coefficients over .90 for performance on the full version subscales. Next, they performed 4 practice blocks of 96 trials on a variant of the McCarthy and Donchin task, described next,⁵ and were trained to balance speed with accuracy in responding. Electrophysiological recordings were not made. Behavioral and electrophysiological data were acquired in 2 subsequent test sessions. Informed consent was obtained from all participants for medical screening and experimental testing using forms approved by the Institutional Review Board.

Experimental task—Subjects viewed 4 row $\times$ 6 column matrices in which LEFT or RIGHT appeared in uppercase font surrounded by number signs (#), by uppercase letters chosen randomly from the set A through G or from the set A through Z, and made either compatible (e.g., left button press to LEFT) or incompatible (e.g., left button press to RIGHT) responses to them with the left or right thumb, each of which rested on a button located on the left and right side of a hand-held response device. Thus, there were three levels of *Noise* (#, A-G, A-Z) and two levels of *symbolic S-R compatibility* (compatible,

⁵The final sample of 68 males was selected from a larger sample of 225 males, all of whom participated in a larger experiment. All of the 225 participants passed the screening process and completed simple and disjunctive versions of the task as well, but this report is restricted to the choice reaction. Two sessions were devoted to data collection in the task reported here and one was devoted to the two other variants of the task. Approximately equal numbers of subjects began testing with the simple/disjunctive tasks, always doing the simple task first. This report is restricted to the choice reaction and to the 68 participants who could be matched most closely on verbal, performance, and full scale IQ scores.

incompatible), all levels of which were mixed randomly within a block of trials. In addition, the location (i.e., row and starting position) of the target word was varied pseudo-randomly on a trial-by-trial basis. That is, on a given trial the target word could appear in any one of the four rows and begin in any one of the appropriate starting positions (LEFT in column 1, 2, or 3; and RIGHT in column 1 or 2), with the constraint that the rows and starting positions occurred about equally often in a block of trials. Every matrix contained a target word shown horizontally in one row, never vertically or diagonally. Examples of the matrices are shown in Figure 1.

A trial was structured as follows: first, the cue word SAME or OPPOSITE appeared in uppercase font at visual fixation for 750 milliseconds (ms); second, 250 ms after its offset (i.e., a foreperiod of 1000 ms) the matrix was shown for 400 ms; third, the subject had 2400 ms to respond; and, fourth, 600 ms later a feedback message appeared on the screen for 1000 ms informing the subject of the speed (RT in ms) and accuracy (correct or incorrect) of his response. A new trial began 3400 ms after the feedback disappeared from the screen. The interstimulus interval was fixed at 8400 ms. Each matrix formed a square that subtended approximately 2.5 degrees of visual angle at a viewing distance of approximately 70 cm. The computer monitor was adjusted such that the subject fixated a continuously displayed dot located at eye level at the centers of the cue word and of the matrix (between rows 2 and 3). Subjects were instructed to balance speed with accuracy in responding, just as they had during practice. They completed 4 blocks of 96 trials in each of the 2 test sessions (a total of 768 trials, with approximately 128 trials per cell). Each test session began with 24 practice trials.

Electrophysiological recordings—ERPs were recorded from electrodes at midline scalp sites Fz, Cz, Pz, and Oz (International Placement (10–20) System; Jasper, 1958) with impedances below 5 Kohms. The EEG was amplified 30,000 times using a Nicolet Model 1A97 EEG System, with the passband set at a low frequency cut-off of .045 Hz (Time Constant of 3.2 seconds; rolloff of 6 dB/octave) and a high frequency cut-off of 30 Hz (rolloff of 12 dB/octave). Electro-ocular (EOG) activity was amplified 7500 times and recorded from electrodes 1 cm above the eyebrow and 1.5 cm below the bottom eyelash of the right eye, aligned vertically with the pupil. The passband for recording EOG and EEG was identical. EEG recordings were monopolar, referenced to linked mastoids; the EOG recording was bipolar. A ground electrode was on the left side of the forehead 3 cm above the left eye. Electrophysiological signals were sampled at 200 Hz for a period of 3500 ms, with a baseline of 100 ms before presentation of the cue word.

Data acquisition and off-line analysis—Data were acquired using a PDP-11/80 based system (Heffley, Foote, Mui, & Donchin, 1985) and were written to nine-track magnetic tape (3M Company) in multiplexed, single-trial format using a nine-track tape drive (Digi-Data). Off-line data analysis occurred on a MicroVAX 3100-40 (Digital Equipment Corporation). Raw single-trial data were corrected for eye movement artifact using the procedure developed by Gratton, Coles, and Donchin (1983), filtered using an optimal linear phase digital filter with the passband set at 6 Hz and the stopband set at 8 Hz (Farwell,

Martinerie, Bashore, Rapp, & Goddard, 1993), and sorted into the experimental cells for data analysis.

P300 latency was estimated using a two-step process. First, the averaged ERP signal for each subject at each factor level was displayed on a computer monitor for visual examination of the component structure and identification of the onset and offset times of the P300 component. Criteria for determining the onset and offset times were, respectively, 5 consecutive digitized point excursions in the positive direction, away from baseline, and the last 5 consecutive digitized point excursions to baseline. These times were identified by moving cursors controlled by a computer algorithm that marked and stored them as the lower and upper edges of the window for identifying the peak of the P300. Second, the time point of the maximum positive value was identified within the time window for each single trial within each factor level for each subject using a computer algorithm designed for that purpose; this value provided the estimate of P300 latency for a given trial. The values found for each trial at each factor level were then averaged to compute the estimated means for each subject. These mean values were then used in the statistical analyses. Our visual examination was to increase the likelihood that a window for the P300 would be established that minimized the frequency with which an early positive peak in the late positive wave that is not the classic P300 would be identified as the maximum positivity (see discussions in McCarthy & Donchin, 1981, and Magliero et al., 1984). It revealed that the window could vary for the time period in which the P300 was estimated to occur, the factor level, and the individual subject. Consequently, we did not use one window for every subject and factor level. Rather, we titrated the windows by factor level and individual for single-trial peak picking. In Table 1 we have listed the mean values for the lower and upper edges of the estimation window (P300 column) as well as the ranges of these edges (Range column) for both age groups across factor levels. Moreover, we did not use the same electrode site for arriving at the estimates. Instead, we determined where P300 was largest using the algorithm described below. It should be noted, however, that estimates were derived preponderantly from the same electrode site (Pz for young adults; typically Cz or Pz for older adults) across subjects.

Data analysis—Univariate repeated measures analyses of variance were completed on the data set (SPSS 19; BMDP 7.0, programs 2V and 4V) with *Age* as the between-groups factor, and *Noise* and symbolic *S-R Compatibility* (SRC) as the within-groups factors.

RESULTS

There are four important concerns that must be met in order to conclude that differences in performance on this task between young and older adults are more reflective of actual age-induced changes in mental processing than they are of factors that may not represent fundamental expressions of these changes.

First, older adults must not have any disease or be taking any medication that compromises central cognitive functions. As we described earlier, our subjects completed extensive medical examinations that excluded individuals who did not meet these criteria. Hence, the

older adults who participated in this study were in excellent health. As a result, it is unlikely that any processing differences we found were secondary to disease or medication effects.

Second, it is important that the two groups are matched on tested IQ to reduce the likelihood that processing differences that emerge can be attributed to differences in intellectual functioning. As is evident in Table 2, the full scale (*FS*), verbal (*V*), and performance (*P*) scores on the WAIS closely approximated one another in the two groups ($F(1,66)$: *FS*, $F = 0.38$, $MSE = 101.43$, $p = .541$; *V*, $F = 0.45$, $MSE = 117.43$, $p = .504$; *P*, $F = 0.11$, $MSE = 125.37$, $p = .738$). Thus, they were matched successfully. As a result, it is unlikely that differences in intellectual functioning, as assessed by the WAIS, contributed to differences in processing speed and accuracy between the two age groups on this task.

Third, it is well-known that older and young adults, if not properly trained in an RT task, tend to adopt different strategic approaches in their performances that cause them to operate at different points on the speed-accuracy trade-off (SATO) function (Welford, 1951): young adults are more willing to sacrifice accuracy for speed, whereas older adults are more willing to sacrifice speed for accuracy. Significant differences between the two groups in their locations on the SATO function would preclude eliminating strategy differences as the source of any putative age effects that might emerge. Our subjects were trained to balance speed with accuracy. Partial support for the effectiveness of this training is found in our observation that overall accuracy rates did not differ between the two groups (*young*—92.56%, *older*—91.88%; *Age*, $F(1,66) = 0.80$, $MSE = 58.41$, $p = .375$). Our analysis did uncover group differences in the costs of incompatibility and of noise on accuracy rates within factor levels that, as we discuss below, support the conclusion that subjects in the two groups generally complied with our instructions.

Fourth, even after having met the first three concerns, the inferential strength of our interpretations of age effects on stimulus and response processing in this task derives ultimately from how closely the pattern of factor effects we found in young adults replicates the pattern found by McCarthy and Donchin (1981) and Magliero et al. (1984). As we discuss next, the pattern we found bore a very close resemblance to the pattern they found.

The replication in young adults

The ERPs elicited in the young adults as they performed this task are illustrated in Figure 2. As can be seen, presentation of the cue word evoked a contingent negative variation (CNV) during the 1000 ms foreperiod that resolved into a series of positive- and negative-going components, including the P300, following presentation of the matrix. The topography of the P300 was estimated in the average ERP for each subject for each experimental condition with a program that identified the distribution of its amplitude across the midline scalp sites and assigned a percentage value to the maximum amplitude of that distribution (with Fz as 0%, Cz as 33%, Pz as 66%, and Oz as 100%). Collapsed across all factor levels the mean distribution of the P300 in young adults was 54%, indicating a parietal orientation like that found by McCarthy and Donchin and Magliero et al. and reported routinely in the literature for young adults. This distribution was unchanged across factor levels (all $ps > .10$).

The patterns of factor effects we found for P300 latency, RT, and accuracy in young and older adults are illustrated in Figure 3, and the means for these measures in each cell in the factor structure, along with the costs of incompatibility and noise, are shown in Table 3. It is readily apparent in Figure 3 that P300 latency and RT increased and accuracy decreased among young adults when incompatible responses were required (*SRC*, $F(1,33)$: *P300*, $F = 44.69$, $MSE = 1791.22$, $p < .0001$; *RT*, $F = 327.01$, $MSE = 2744.94$, $p < .0001$; *Acc*, $F = 34.31$, $MSE = 15.75$, $p < .0001$) and when letters surrounded the target (*Noise*, $F(2,66)$: *P300*, $F = 80.22$, $MSE = 12584.60$, $p < .0001$; *RT*, $F = 473.87$, $MSE = 1733.22$, $p < .0001$; *Acc*, $F = 18.65$, $MSE = 15.75$, $p < .0001$). It is also apparent that the costs of incompatibility on both P300 latency and RT were invariant across noise levels (*SRC* $\times$ *Noise*, $F(2,66)$: *P300*, $F = 0.10$, $MSE = 582.93$, $p = .906$; *RT*, $F = 0.05$, $MSE = 379.25$, $p = .955$). Indeed, as can be seen in Table 3, the costs of incompatibility on RT and P300 latency were nearly identical at each level of noise, whereas the cost on accuracy was larger for # than for letter matrices (*SRC* $\times$ *Noise*, $F(2,66) = 4.99$, $MSE = 5.13$, $p = .010$). Magliero et al., it should be noted, found an invariant cost of incompatibility on accuracy across noise levels. McCarthy and Donchin reported only the overall accuracy (91.7%). Thus, the pattern of factor effects we found on RT replicates that reported by McCarthy and Donchin and Magliero et al.; and like the latter included a significant cost of incompatibility on P300 latency. Hence, the last and most important concern has been met, laying the foundation for the comparative analysis that we describe next. This description begins with a full presentation of the results of the speed-accuracy trade-off analysis.

The comparative analysis

SATO—Our concern that older and young adults operated at similar points on the SATO function in this task received partial support, as we indicated earlier, in our finding comparable overall accuracy levels in the two age groups. Other factor effects added further support. As can be seen in Figure 3 and Table 3, the cost of incompatibility on accuracy was larger among young than older adults (*SRC* $\times$ *Age*, $F(1,66) = 8.52$, $MSE = 14.18$, $p = .005$). This difference occurred because young adults were more accurate than older adults when making compatible responses while being equally accurate when making incompatible responses (*Simple Effects*, $F(1,66)$: 94.19 vs. 92.42%, $F = 4.91$, $MSE = 32.34$, $p = .030$; 90.93 vs. 91.34%, $F = 0.02$, $MSE = 42.22$, $p = .897$). Hence, there was a larger fall-off in accuracy among young adults. Similarly, the increased cost of noise on accuracy among older adults (*Noise* $\times$ *Age*, $F(2,132) = 12.84$, $MSE = 21.40$, $p < .0001$) was produced by their being more accurate than young adults when responding to targets in a # surround while being less or tending to be less accurate when responding to targets in an A-G or A-Z surround (*Simple Effects*, $F(1,66)$: # 97.47 vs. 94.87%, $F(1,66) = 22.82$, $MSE = 10.09$, $p < .0001$; A-G 89.53 vs. 91.97%, $F = 6.36$, $MSE = 44.40$, $p = .014$; A-Z 88.65 vs. 90.84%, $F = 3.62$, $MSE = 45.11$, $p = .062$). As can also be seen in Figure 3, this pattern did not vary in any important way across levels of compatibility (*SRC* $\times$ *Noise* $\times$ *Age*, $F(2,132) = 0.54$, $MSE = 6.91$, $p = .584$).

In general, then, the pattern of performance accuracy indicated that both young and older adults complied with the task instructions to balance speed with accuracy in their decision-making. The marginally higher accuracy level among older adults when the target stimulus

was easy to discriminate (i.e., a # surround) suggests, however, that young adults may have traded some accuracy for speed when they could identify the target quickly, particularly when they made incompatible responses. Nonetheless, most evident in these results is that a matrix of letters had a greater debilitating effect on the accuracy with which older than young adults could locate and identify the target.

Age-related differences in processing speed—The ERPs elicited in the older adults are shown in Figure 4. In older adults, like young adults, presentation of the cue word evoked a contingent negative variation (CNV) that resolved into a series of positive- and negative-going components, including the P300, after the matrix appeared. Consistent with the literature, the P300 recorded from older adults had a centrally-oriented distribution along the midline scalp that departed significantly from the parietal orientation of young adults (41 vs. 54%; *Age*, $F(1,66) = 5.10$, $MSE = 3492.51$, $p = .027$); this difference between the two age groups was invariant across factor levels (all $ps > .10$).

The results of the analyses on the mean and log-transformed values for RT and P300 latency are shown in Table 4. Note that the main effects of each experimental factor for each measure are strengthened modestly by the log transform. Most noteworthy, however, are the effects of this transformation on the first- and second-order interactions. As expected, both analyses revealed that P300 latency and RT increased when incompatible responses were required and when responses were made to targets embedded in letter matrices (see Figure 3, Tables 3 and 4), and both P300 latency (796.34 vs. 626.09 ms) and RT (923.95 vs. 696.91 ms) were longer among older than young adults (see Table 4). Also, as expected, the mean analyses revealed decreases in accuracy when incompatible responses were required and when targets were embedded in noise matrices (*SRC*, $F(1,66) = 33.78$, $MSE = 14.18$, $p < .0001$; *Noise*, $F(2,132) = 75.93$, $MSE = 21.40$, $p < .0001$). Most telling are the differences in patterns of age-related factor effects between the two analyses.

The cost of incompatibility in the mean analysis was marginally larger on P300 latency in young than older adults, while it did not differ between the two groups on RT (*SRC* $\times$ *Age*, $F(1,66)$: P300, $F = 4.31$, $MSE = 1633.39$, $p = .042$; RT, $F = 0.60$, $MSE = 3180.72$, $p = .44$). However, the log N analysis uncovered both a cost on RT that was significantly larger among older than young adults and a much more robust cost on P300 latency among young adults (*SRC* $\times$ *Age*, $F(1,66)$: RT, $F = 5.30$, $MSE = .005$, $p = .024$; P300, $F = 10.84$, $MSE = .003$, $p = .002$). In contrast, the cost of noise was larger on mean RT among older than young adults, whereas the cost on mean P300 latency was comparable (*Noise* $\times$ *Age*, $F(2,132)$: RT, $F = 22.86$, $MSE = 2311.29$, $p < .0001$; P300, $F = 0.20$, $MSE = 12813.02$, $p = .816$). The costs of noise did not differ, however, between the two age groups for either measure in the log N analysis (*Noise* $\times$ *Age*, $F(2,132)$: RT, $F = 1.03$, $MSE = .003$, $p = .360$; P300, $F = 2.21$, $MSE = .030$, $p = .114$); that is, the significant interaction found in the mean RT analysis reflected only generalized slowing.

Additive relationships were found in the mean analyses between compatibility and noise for both P300 latency and RT (*SRC* $\times$ *Noise*, $F(2,132)$: P300, $F = 0.40$, $MSE = 633.62$, $p = .669$; RT, $F = 2.29$, $MSE = 566.31$, $p = .105$). However, the log N analysis yielded a highly significant interaction between compatibility and noise for RT in which the cost of

incompatibility was revealed to increase as noise levels increased ($SRC \times Noise$, $F(2,132)$: RT, $F = 21.97$, $MSE = .001$, $p < .0001$; # 129.98 ms, A-G 140.20 ms, A-Z 140.91 ms) and this increase was restricted to older adults ($SRC \times Noise \times Age$, $F(2,132) = 3.16$, $MSE = .001$, $p = .046$; see Table 4). Indeed, separate mean and log N analyses on the RT data of the older adults confirmed this increase ($SRC \times Noise$, $F(2,66)$: mean, $F = 3.00$, $MSE = 753.37$, $p = .056$; log N, $F = 3.85$, $MSE = .001$, $p = .026$). However, the effect of age on the combined influences of compatibility and noise was less transparent in the log N analysis of P300 latency. The first-order interaction was marginally significant ($SRC \times Noise$, $F(2,132) = 3.31$, $MSE = .001$, $p = .040$), with the cost of incompatibility on P300 latency increasing from # to A-G and then decreasing from A-G to A-Z noise (# 30.62 ms, A-G 32.05 ms, A-Z 28.28 ms), but differences in age appeared to have no influence on this interaction ($SRC \times Noise \times Age$, $F(2,132) = .14$, $MSE = .001$, $p = .873$). Nonetheless, examination of Table 3 suggests that, unlike young adults whose costs remain constant across noise levels, the costs in older adults appear to decrease as noise increases. However, separate mean and log N analyses on the P300 latency data of older adults indicated that these effects were additive ($SRC \times Noise$, $F(2,66)$: mean, $F = .67$, $MSE = 684.32$, $p = .515$; log N, $F = 1.35$, $MSE = .001$, $p = .266$).

DISCUSSION

The pattern of factor effects we found among young adults in this task replicates, with minor variations, the pattern reported by McCarthy and Donchin (1981) and Magliero et al. (1984). Like these investigators we found costs of incompatibility and noise on RT and P300 latency that were additive. Like Magliero et al., but unlike McCarthy and Donchin, we found a significant cost of incompatibility on P300 latency. Unlike Magliero et al., who found additive costs of incompatibility and noise on accuracy, we found a reduction in cost when targets were embedded in noise matrices. This close replication provided experimental justification for assessing the differential influences of older age on target identification and response selection processes in this task. Our analyses of these influences in medically very healthy older males yielded well-known and novel age effects, in support of both our working hypothesis and of refinements in it.

Both the mean and log-transformed analyses revealed, as is consistently reported in the literature, longer latency P300s and slower RTs among older than young adults across all factor levels. Patterns of age influences on factor effects were brought into relief, however, by the log N analyses. They exposed a robust age-related dissociation in the cost of incompatibility on P300 latency and RT and an age-related association in the cost of noise on P300 latency and RT. Specifically, the costs of incompatibility on RT and P300 latency were, respectively, larger, as we predicted, and smaller, in contrast to our prediction, among older than young adults. To our knowledge, this combined effect is novel. In contrast, as we anticipated, the costs of noise on both RT and P300 latency were comparable in the two age groups. This association, although not novel, strengthens previously observed associations because it was produced in a task that induces selective influences on target identification and response selection processes, reflected in RT, that are interpretable within a well-established statistical-conceptual framework, as we argued in the Introduction. We also observed that, like young adults, the cost of incompatibility on P300 latency did not vary

with noise in older adults, as we predicted, but that, unlike young adults, the cost on RT increased among older adults as noise increased, in contrast to our prediction. To our knowledge, the latter is a novel finding.

Speculations on the contribution of response-related processing speed to P300 latency

Our finding that variations in S-R compatibility influenced P300 latency is consistent not only with the finding of Magliero et al. (1984) but also with findings, some of which were reviewed in the Introduction, that variations in S-R mapping influence P300 latency. The extent to which these variations have an influence has been controversial, however, since the early 1980s when, in contrast to McCarthy and Donchin (1981), Ragot and Renault (1981) reported that variations in spatial S-R compatibility influenced P300 latency (see also Ragot, 1984). Exchanges between Magliero et al. (1984) and Ragot and Renault (1985) suggested that there was either a difference in the influence of variations in spatial and symbolic compatibility on P300 latency (see discussion in Ragot, 1990) or that spatial compatibility might be re-conceptualized as a type of spatial conflict in which stimulus evaluation processes are engaged (Magliero et al., 1984). Subsequent work by Ragot and Lesevre (1986) and by Pfefferbaum et al. (1986) also revealed influences of variations in spatial and symbolic S-R compatibility, respectively, on P300 latency. Indeed, the controversy over the degree to which P300 latency indexes stimulus-related processing time uncontaminated by response-related processing has continued to re-surface over the years.

This controversy is embodied in the work of Falkenstein and colleagues (e.g., Falkenstein, Hohnsbein, & Hoorman, 1993, 1994; Hohnsbein, Falkenstein, & Hoorsman, 1995; Hohnsbein, Falkenstein, Hoorsman, & Blanke, 1991) who argued that the P300 comprises two subcomponents, one reflecting stimulus evaluation, the “P-SR”, and the other response selection, the “P-CR”. They contend that P300 latency measures, to visual stimuli in particular, confound the two subcomponents and that the presence of the “P-SR” interferes with peak picking. Dien, Spencer, and Donchin (2004) demonstrated, however, that the P-SR conforms to the P3a/novelty P3 and the P-CR conforms to the classic P300 (see Verleger, Ja kowski, & Wascher, 2005, for an experimental dissection of the P3a and P300, or P3b, that addresses this issue directly; also see Fjell et al., 2009). Moreover, they argued that the task used by Falkenstein et al. did not differentiate stimulus categorization from response selection, as did the tasks used by Kutas et al. (1977), McCarthy and Donchin (1981), and Magliero et al. (1984). Dien et al. concluded that “...the P300 (or P-CR as termed by Falkenstein and colleagues) mainly correlates with stimulus categorization time, not with response selection time, although a small percentage of the P300 latency variance does appear to be correlated with response selection (Magliero et al., 1984)”. Our findings are consistent with this conclusion, certainly as it pertains to the matrix task.

Of interest in this context is the observation by van der Lubbe and Verleger (2002) that the magnitude of the Simon effect is comparable on P300 latency and RT (~25 ms) in young adults. Indeed, the work of Verleger et al. (2005) indicates that the contributions of stimulus- and response-processing demands to P300 latency are approximately equivalent in a Simon task, suggesting that “...P3b reflects a function that bridges perceptual processing with response processing” (p. 177) (also see O’Connell, Dockree, & Kelly, 2012). As we argue

and elaborate later, we agree with this conclusion. It should be noted, however, that the matrix task imposes processing demands on the subject that exceed those of the Simon task with regard to both target identification and response selection and this difference has implications for the relative contributions of stimulus and response processing to P300 latency. It should also be emphasized, as discussed by McCarthy and Donchin and Magliero et al., that the influence of variations in symbolic S-R compatibility on P300 latency in the matrix task are small compared to that of variations in noise. The cost of incompatibility on P300 latency we found among young adults, 40 ms, is decidedly smaller than the costs of noise for the A-G, 192 ms, and the A-Z, 226 ms, surrounds. Hence, P300 latency appears to be influenced by variations in processes related to the response output decision, but the influence in this mental reaction is small relative to that produced by variations in target identification demands. It is against this backdrop that we interpret the age effects we found.

Similarities and departures from previous research findings

There is convergence in the pattern of effects we found on the conclusion that older age has its most dramatic effect on performance in the matrix task at the juncture in the decision-making process where a stimulus input is transformed into a response output. Before offering a more complete interpretation of our results, however, it is important to discuss differences and similarities in the pattern of effects reported by us and by Smulders et al. (1999) because their experimental design and ours closely resemble one another. Both tasks were designed to partition processing within the conceptual framework of Sternberg's (1969) AFM using directional words ("link", "rech", "left", "right") as the targets and varying the symbolic compatibility of the response signaled by each word. Smulders et al. found that the increases in both RT and P300 latency were larger in older than in young adults when target encoding was made more difficult, the cost of incompatibility did not differ between the two groups on P300 latency, and the cost of incompatibility was larger on RT in older than young adults. We found, however, that the cost of incompatibility on P300 latency was smaller in older than in young adults, but that, like Smulders et al., the cost on RT was larger in older than in young adults. Moreover, we found that the cost of incompatibility on RT, but not on P300 latency, increased when the noise level in the target surround increased, whereas Smulders et al. found that the effects of variations in stimulus quality and S-R compatibility were additive on both RT and P300 latency. How might we account for the differences in factor effects reported in these two studies?

Variations in methodology may have been contributory.⁶ We mixed compatible and incompatible responses within a block of trials (i.e., SRC was mixed), whereas in Smulders et al. subjects made only compatible or only incompatible responses within a block of trials (i.e., SRC was blocked). They speculated that this difference, mixed versus blocked presentations, provides one possible explanation for their finding a significant cost of incompatibility on P300 latency when McCarthy and Donchin (1981) did not. However, like us, Magliero et al. (1984) mixed compatible and incompatible responses within a block and found a cost of incompatibility on P300 latency. Consequently, blocking versus mixing of the two response types is unlikely to be the source of any difference in effects between our findings and those of Smulders et al.

The most important source of the departures may be variations in processing demands between the two tasks. In the Smulders et al. task, the ease with which an isolated target stimulus, presented at visual fixation, could be encoded was varied either by degrading it or leaving it intact. In contrast, in the McCarthy and Donchin task subjects must search a matrix to locate and identify a target stimulus, the difficulty of which varies with the presence or absence of letters in the target surround. In addition, Smulders et al. used a target duration (1000 ms) that is longer than that used in the matrix task (400 ms), perhaps making target identification even more difficult for our subjects than for theirs. Thus, greater processing demands may have been imposed in the matrix task. Such a difference is certainly suggested in differences in the values and ranges of P300 latency, RT, and accuracy levels in the two studies. P300 latency and RT ranged, respectively, from 440 to 615 ms and from 450 to 740 ms in Smulders et al., whereas they ranged from 467 to 882 ms and from 507 to 1107 ms in this study. Accuracy levels ranged from 94.10 to 99.00% in Smulders et al. and from 88.27 to 98.35 in our study. Some questions arise within the context of these putative differences in processing demands, responses to which may help explain differences in factor effects.

First, how do we reconcile the greater cost of degradation on P300 latency in elderly adults found by Smulders et al. with our finding a comparable increase in P300 latency among the two age groups when letters rather than # comprised the target surround? This difference in factor effects is consistent with findings that demonstrate a greater decline of early stimulus encoding than of intermediate stimulus location/identification processes in older age. However, the complexity of these early vulnerabilities is suggested in the findings of Pfefferbaum and Ford (1988) and Verleger et al. (1991), for example, that reveal preservation of early stimulus encoding among the elderly under certain experimental

⁶Although Smulders et al. tested 15 older and 13 young men their analyses were restricted almost entirely to data from 11 of the older and 12 of the young adults because no discernible P300s could be identified in the ERPs of the excluded subjects. We tested 34 young and 34 older men. Hence, differences in power may be partially explanatory of differences found in the two studies. Consistent with this speculation is the finding by Smulders et al. that a tendency ($p = .10$) for the cost of incompatibility to be larger on RT among older than young adults was transformed into a significant interaction ($p < .05$) when the data of the excluded subjects were included in the analysis; an outcome attributed by the authors to an increase in power with the added subjects. Recall, the cost of degradation was larger in older than in young adults for both P300 latency and RT. Inspection of Figure 1 in their paper suggests, however, that the cost of incompatibility on P300 latency may have been reduced among the elderly when the stimulus was degraded (estimated from Figure 1 to be about 40 and 15 ms for non-degraded and degraded targets, respectively). Failure to find a significant interaction may be a product of the same reduction in power that prevented the increased cost of incompatibility on RT in older adults from being revealed. This possibility is suggested in the p value of .13 for the Age $\times$ Stimulus Quality $\times$ S-R Compatibility interaction for P300 latency. Since subjects were eliminated from the analysis because of small or non-identifiable P300s, none could be added to increase its power.

conditions, and of Verleger et al. (1991) who found comparable effects of variations in stimulus intensity, presumably influencing early stimulus encoding, on P300 latency among young and older adults in conjunction with larger effects among the elderly on RT.

Second, how do we explain a larger increase in the cost of degradation, found by Smulders et al., and of noise, found by us, on mean RT among older than young adults? Our explanation emerges from concomitant influences observed on mean P300 latency. The pattern found by Kok's group in the Eriksen task and by us in the matrix task of a comparable increase in P300 latency coupled with a larger increase in RT when the target stimulus was difficult to identify is consistent with the view that processes manifest in P300 that represent intermediate elements of stimulus processing are relatively spared, whereas those that are either subsequent to or independent of P300, and reflected in RT, are relatively compromised. Thus, it is our contention that slowing of processes related to the response output decision and/or generation of the response output command is expressed in the increase in mean RT. This conclusion is buttressed by the finding of Smulders et al. that the cost of symbolic incompatibility, thought to delay response selection, is larger on RT among the elderly, and by our finding that this slowing in RT increased as the difficulty in locating and identifying the target increased. Most importantly, our reasoning is supported by the finding that the larger increase in noise effects on mean RT among older adults was eliminated by the log N transformation. The finding by Smulders et al. that degradation of the target stimulus produced a larger slowing of P300 latency among older than young adults does not argue against this conclusion. Rather, as discussed in the preceding paragraph, it supports work identifying the vulnerability of early stimulus encoding processes in older age.

Third, how do we explain the additive effects of variations in stimulus quality and S-R compatibility on mean RT found by Smulders et al. for both young and older adults, and the additive effect of variations in noise and S-R compatibility on mean RT found among our young adults in the context of an overadditive interaction among our older adults? According to AFM reasoning, these additive factor effects support the conclusion that two independent stages of processing, stimulus encoding and response selection, were influenced in both young and older adults in the Smulders et al. task; and two independent stages, target identification and response selection, were influenced in young adults in our task. However, our finding an overadditive interaction on mean RT among older adults that was strengthened by the Log N transformation supports the conclusion that either one stage is influenced by both factors in older adults or two stages of processing overlap in older adults. Given the pattern of effects in young adults, support is provided, in our view, for overlapping processing.

Our reasoning is as follows. Variations in target quality influence very early stimulus encoding processes, whereas variations in noise level in the target surround influence later target location and identification processes. Encoding occurs sufficiently early in the processing of the stimulus, perhaps even when slowed by degradation, to be completed before response-related processes are engaged. Hence, it may delay their onset, but completion of encoding processes, even when delayed, probably does not overlap the beginning of response-related processes. However, target location and identification are

proximal to them. Indeed, identification of the target provides the essential transition to response selection processes (e.g., see van der Molen, Bashore, Halliday, & Callaway, 1991). Consequently, when target identification processes are slowed sufficiently, as they may be among the elderly by the presence of letters in the target surround (i.e., slowing is added to an already slow processing system), response-related processes may be initiated before identification of the target has been completed. Thus, target processing may continue after response processes have been activated and this overlap may produce the increase in the cost of incompatibility on RT among older adults as it becomes more difficult to locate and identify the target stimulus.

Fourth, how do we explain the reduced cost of incompatibility on mean and log N P300 latency we found in older adults when Smulders et al. found the mean cost to be comparable in the two age groups? Our reasoning follows that developed in the third response. Namely, when overall target identification processes are slowed sufficiently response-related processes may be initiated before identification of the target has been completed producing an overlap that may confound the two processes and, in so doing, produce either a real or apparent reduction in the cost of incompatibility on P300 among older adults. In contrast, slower target encoding processes among older adults may have been completed well before response output decisions were made and, as a result, would not influence them.

How specific is process-specific slowing?

We took the position in the Introduction that the task for researchers in cognitive aging is to isolate the components of rapid decision-making that are differentially influenced by advancing age and to determine their sensitivity to variations in task demands. Our data point very specifically to response selection processes as being differentially altered by age on the matrix task. This position differs from the conclusions drawn by Yordanova et al. (2004), Falkenstein et al. (2006), Kolev et al. (2006), and Wild-Wall et al. (2008). Based on findings from a 4-choice RT task Yordanova et al. concluded that "...in the currently used tasks, behavioural slowing is produced by stages later than response selection" (p. 359) and "...is localized primarily at the level of motor response generation" (p. 359); and Falkenstein et al. echoed this conclusion by asserting that "...aging-related delay occurred during the central stage of response-generation, while the timing of preceding stimulus processing and response selection mechanisms were virtually unaffected" (p. 27). Support for this conclusion came from their finding comparable sLRP onset latencies among the two age groups in conjunction with earlier onsets relative to the final response, increased amplitudes, and steeper rise times to the peaks of the rLRP and a response-locked MRP measured at a central scalp site contralateral to the moving digit among older adults.

A slightly broader view of the slowing was offered by Wild-Wall et al. who reported a pattern of effects that differed somewhat from those reported by Kok's group using variants of the flanker task in which the flankers appeared 100 ms before or at the same time as the target. Like Kok's group, they found that RT, P300 latency, sLRP onset latency, and the interval between the onset of the LRP to the response were longer among elderly than young adults, but, unlike Kok's group, did not find larger increases in latency among the elderly for either sLRP onset latency or RT when they responded to arrays with flankers that signaled

the response opposite that signaled by the target.⁷ Recall that an age-related increase in sLRP onset latency was not found in the 4-choice reaction. Wild-Wall et al. concluded that the earlier onset of the rLRP (relative to the response) among older subjects "...suggests that the main part of age-related slowing can be explained by prolonged motor preparation beyond response selection ...", whereas the later onset of the sLRP "...indicates also a slower information transmission from visual to motor areas..." which "...also contributes to a deficit in stimulus-response mapping, which in turn impairs response selection" (p. 80). Departures in factor effects from Kok's group, it should be noted, may reflect methodological differences suggestive of the task-dependent nature of age effects. Unlike Kok's group who used traditional horizontally-aligned stimulus arrays, Wild-Wall et al used vertically-aligned arrays and their instructions placed moderate pressure on subjects to be fast (600 ms RT limit) which yielded differences in speed-accuracy trade-offs between two age groups.

Speculations on the stage structure of speeded processing in young and older adults

In a quantitative re-analysis of Donders (1868–1869) Law of the Choice Reaction, Teichner and Krebs (1974) reasoned that choice reaction time comprises four components: the time required to encode a stimulus and the simple reaction time to it (considered by them to represent basic neural transmission time), the time to discriminate between stimulus codes when more than one is involved, the time related to translating the final stimulus code into the appropriate response code (i.e., S-R translation), and the total time required for selection of the response mapped to a particular response code (i.e., response selection). In a series of simulations they demonstrated that early in practice the largest proportion of time in the choice reaction is consumed by S-R translation processes, but that after extensive practice (simulated to be over 50,000 trials) these processes consume a very small amount or none of the time and response selection processes consume the balance. If this is the case, our subjects were given a tiny fraction of the practice trials (496) required to achieve this end and therefore may have performed the task with S-R translation processes constituting a large proportion of response-related processing time, especially when incompatible responses were required.

It is our contention that S-R translation and response selection processes have typically not been distinguished in the literature and patterns of results interpreted as reflective of factor effects on response selection may actually reflect factor effects on either S-R translation, response selection, or some combination of these two processes. In our earlier discussion we used the term "response selection" to maintain consistency with the literature. However, at this point, following Teichner and Krebs, we distinguish S-R translation from response selection processes. To begin our discussion, we return to Smulders et al. (1999) and describe the model they presented, shown in Figure 5A, in explanation of their results.

⁷When flankers appeared 100 ms before the target Wild-Wall et al. found that the onset of the sLRP was later in older than in young adults only for incorrect, not correct, responses to a target that signaled the response opposite that signaled by the flankers, whereas it was later in older than in young adults when correct responses were made on trials in which the flankers and target signaled the same response (they did not differentiate correct from incorrect patterns for the simultaneous onset condition).

In an effort to reconcile their finding an additive effect of variations in stimulus quality and S-R compatibility on P300 latency, an unexpected finding, with an additive effect on RT, an expected finding, Smulders et al. reasoned that there was an intermediate stage of processing between stimulus encoding and response selection that was influenced by variations in S-R compatibility. However, they did not suggest a name for that stage. The stimulus encoding stage and this unnamed stage were thought by them to precede the moment when P300 latency is determined. They reasoned that variations in age and stimulus quality influenced the encoding stage, whereas variations in age and S-R compatibility influenced the response selection stage.

Our position is that the S-R translation stage is a strong candidate for the unnamed stage. Our data and those of Smulders et al. suggest the stage structure depicted in Figure 5B for young adults. The additive influences in young adults of variations in noise and S-R compatibility on P300 latency (increases when targets were difficult to discriminate and responses were incompatible) reveal, according to Sternberg's (1969) additive factors reasoning, the engagement of different stages of stimulus and response processing. We are speculating that these two stages are target identification and S-R translation. Elicitation of the P300 may represent activation of the target identification process as well as the transfer of this information, the identity of the word associated with a compatible response, either to the S-R translation stage from which it is then conveyed to the response selection stage or directly to the response selection stage (for related conceptualizations see O'Connell et al., 2012; Verleger, 1997; Verleger et al., 2005). Recall, following Teichner and Krebs (1974), that the highly overlearned (i.e., extensively practiced) compatible response may engage the response selection stage directly (i.e., without the need for S-R translation). However, the newly required incompatible response must engage the S-R translation stage prior to activating the response selection stage. Thus, the substantially larger influence of making an incompatible response on RT than on P300 latency may result from the need to inhibit selection of the prepotent compatible response following translation of the stimulus code into the opposite response code so that the correct, but incompatible, response can be selected and executed (the small negative deflection or "dip" in the sLRP first observed by Gratton, Coles, Sirevaag, Eriksen, & Donchin, 1988, supports this inference, as do subsequent similar observations by, for example, Osman, Bashore, Coles, Donchin, & Meyer, 1992). That the increases in P300 latency and RT produced by the presence of letters in the matrix surround were roughly comparable, perhaps even larger for P300 latency, in young adults (e.g., # $\rightarrow$ A-G: P300 192 ms; RT 161 ms), whereas the cost of incompatibility was appreciably larger on RT than on P300 latency (P300 40 ms; RT 132 ms), suggests that convergence on the specific response output decision dominated processing as it neared its completion. The additive factor effects on RT may, therefore, reflect a dissociation of stimulus and response processing as the response output command is being prepared and executed.

How might age alter this stage structure? The addition of letters to the surround produced comparable slowing of P300 latency in the two age groups (192 and 186 ms for the young and older adults, respectively), while the cost of incompatibility on P300 latency was smaller among the older adults (22 vs. 40 ms). The former finding indicates that the

additional time required to identify the target when it is difficult to locate is comparable in the two age groups. However, since these target-related processes are embedded in a processing system that is slowed among the elderly at this level (as reflected in the overall P300 latency [*older*, 797 ms; *young*, 626 ms]), the influence of incompatibility on P300 latency may have been obscured, as we argued earlier. Recall, the relationship between stimulus and response processing changed in the elderly when the reaction approached its end, as revealed in the overadditive interaction on RT between these two factors. The increase in RT produced by the addition of letters to the matrix surround was appreciably larger among the elderly than the young (237 ms vs. 161 ms) and the cost of incompatibility was increased among the elderly when letters surrounded the target (# 128 ms, A-G 147 ms, A-Z 149 ms), while it remained unchanged among the young (# 132 ms, A-G 134 ms, A-Z 133 ms). Thus, the dissociation in stimulus and response processing that characterized the young adult information processor near the end of processing did not characterize the older information processor. Where the complexity of the stimulus input had no differential effect on the influence of variations in S-R compatibility in the young adult, it did in the older adult.

It appears that older age produces not only quantitative changes in the rate of processing, but also qualitative changes in the relationship between stimulus and response processing over the later portions of a complicated choice reaction, perhaps a growing interdependence as first speculated by Birren and colleagues (e.g., Birren, 1965; Birren et al., 1980). When the older adult was obliged to make an effortful stimulus-response translation (i.e., execute an incompatible response) the need to search the matrix for the target when it was embedded in a letter surround may have delayed target identification sufficiently that translation of the stimulus code into the opposite response code during the S-R translation stage was similarly delayed and could not be completed before the response selection stage was activated by the prepotent compatible response. In turn, the compatible response, once activated, had to be inhibited after successful translation of the stimulus code into the opposite response code prior to activation and execution of the incompatible response, a process that may take longer and be more effortful in older than in young adults, as suggested in Wild-Wall et al.'s (2008) observation that the dip in the sLRP on trials in which the target and flankers signal opposite responses has a later onset and larger amplitude among older than young adults. If so, a *serial* sequence of processing in young adults may have been transformed into an *overlapping* sequence among the elderly shortly before the correct response output command could be initiated. Thus, an overlap in processing between the S-R translation and response selection stages may occur in the older but not in the young adult information processor. However, the relative contributions to this interactive effect of differential changes induced by older age on these two stages of processing or later stages of response processing like response generation and execution cannot be deduced from our experiment because it was not designed to differentiate them.

CONCLUDING COMMENTS

The pattern of age effects exposed in the matrix task on RT and P300 latency indicate that with older age comes a declination in the speed with which a stimulus code can be translated into a response code that then guides selection of a goal-directed response. However, the

specificity of the inferences we can draw from the results is limited by our having restricted the recordings of brain electrical activity to midline scalp sites and to the analysis of P300 latency. Of particular value will be analyses of factor effects over a larger range of scalp sites on movement-related brain potential activity, such as that of the stimulus- and response-locked lateralized readiness potentials, in conjunction with those on the latencies of ERP components elicited earlier than the P300 to isolate differential effects of aging on early stimulus processing and later response processing, and how these effects interact with those on intermediate stimulus processing. Analyses of this type will permit dissection of age influences on stimulus and response factors to be accomplished with greater precision than we were able to achieve. In addition, the extent to which patterns of age effects can be generalized to the broader older population may be constrained by our having tested males, not females. Nonetheless, the findings that emerged in this study suggest the promise of using McCarthy and Donchin's matrix task to contribute to the articulation of process-specific changes in mental processing speed induced by older age.

Acknowledgments

This research was supported by: (i) grants [AG04581 (TRB)] and [K23AG028750 (SAW)] from the National Institute on Aging (the content is solely the responsibility of the authors and does not necessarily represent the official views of the National Institute on Aging or the National Institutes of Health); (ii) The Netherlands Organization for Scientific Research (KRR); and (iii) the Centre Nationale Recherche Scientifique (JMM). The authors thank Brian Foote for developing the data acquisition software, Dr. Lee Greenspon for conducting the medical examinations, Dr. Philip Weiser for performing the exercise stress tests, Dr. Grant Morris for thoughtful comments on earlier versions of this manuscript, and Barry LaPointe for preparation of the ERP figures.

References

- Allen PA, Ashcraft MH, Weber TA. On mental multiplication and age. *Psychology and Aging*. 1992; 7:536–545. [PubMed: 1466822]
- Allen PA, Lien MC, Murphy MD, Sanders RE, Judge KS, McCann RS. Age differences in overlapping-task performance: Evidence for efficient parallel processing in older adults. *Psychology and Aging*. 2002; 17:505–519.
- Allen PA, Smith AF, Groth KE, Pickle JL, Grabbe JW, Madden DJ. Differential age effects for case and hue mixing in visual word recognition. *Psychology and Aging*. 2002; 17:622–635. [PubMed: 12507359]
- Allen PA, Smith AF, Vires-Collins H, Sperry S. The psychological refractory period: Evidence for age differences in attention time-sharing. *Psychology and Aging*. 1998; 13:218–229. [PubMed: 9640583]
- Amrhein PC, Theios J. The time it takes elderly and young individuals to draw picture and write words. *Psychology and Aging*. 1993; 8:197–206. [PubMed: 8323724]
- Band GPH, Kok A. Age effects on response monitoring in a mental-rotation task. *Biological Psychology*. 2000; 51:201–221. [PubMed: 10686366]
- Band GPH, Miller J. Mental rotation interferes with response preparation. *Journal of Experimental Psychology: Human Perception and Performance*. 1997; 23:319–338. [PubMed: 9103997]
- Band GPH, Ridderinkhof KR, Segalowitz S. Explaining neurocognitive aging: Is one factor enough? *Brain and Cognition*. 2002; 49:259–267. [PubMed: 12139953]
- Basak C, Verhaeghen P. Subitizing speed, subitizing range, counting speed, the Stroop effect, and aging: Capacity differences and speed equivalence. *Psychology and Aging*. 2003; 18:240–249. [PubMed: 12825774]
- Bashore TR, Osman A, Heffley EF. Mental slowing in elderly persons: A cognitive psychophysiological analysis. *Psychology and Aging*. 1989; 4:235–244. [PubMed: 2789753]

- Bashore, TR.; Ridderinkhof, KR.; van der Molen, MW. Lifespan studies of mental chronometry: Insights derived from chronopsychophysiology. In: Raz, N., editor. *The other side of the error term*. Amsterdam: North-Holland; 1998. p. 197-258.
- Bashore, TR.; Smulders, F. Do general slowing functions mask local slowing effects? A chronopsychophysiological perspective. In: Allen, PA.; Bashore, TR., editors. *Age differences in word and language processing*. Amsterdam: North-Holland; 1995. p. 391-426.
- Besic E, Kramer AF, Boot WR. Age-related differences in visual search in dynamic displays. *Psychology and Aging*. 2007; 22:67–74. [PubMed: 17385984]
- Birren, JE. Age changes in the speed of behavior: Its central nature and physiological correlates. In: Welford, AT.; Birren, JE., editors. *Behavior, aging, and the nervous system*. Springfield, IL: Charles C. Thomas; 1965. p. 191-216.
- Birren, JE.; Woods, AM.; Williams, MV. Behavioral slowing with age: Causes, organization, and consequences. In: Poon, LW., editor. *Aging in the 1980s: Psychological issues*. Washington, DC: American Psychological Association; 1980. p. 293-308.
- Brinley, JF. Cognitive sets, speed and accuracy of performance in the elderly. In: Welford, AT.; Birren, JE., editors. *Behavior, aging, and the nervous system*. Springfield, IL: Charles C. Thomas; 1965. p. 114-149.
- Bucur B, Allen PA, Sanders RE, Ruthruff E, Murphy MD. Redundancy gain and coactivation in bimodal detection: Evidence for the preservation of coactive processing in older adults. *Journal of Gerontology: Psychological Sciences*. 2005; 60B:P279–P282.
- Burke DM, White H, Diaz DL. Semantic priming in young and older adults: Evidence for age constancy in automatic and attentional processes. *Journal of Experimental Psychology: Human Perception and Performance*. 1987; 13:79–88. [PubMed: 2951489]
- Castel AD, Balota DA, Hutchison KA, Logan JM, Yap MJ. Spatial attention and response control in healthy younger and older adults and individuals with Alzheimer's disease: Evidence for disproportionate selection impairments in the Simon task. *Neuropsychology*. 2007; 21:170–182. [PubMed: 17402817]
- Cerella J. Information processing rates in the elderly. *Psychological Bulletin*. 1985; 98:67–83. [PubMed: 4034819]
- Cerella, J.; Poon, LW.; Williams, DM. Age and the complexity hypothesis. In: Poon, LW., editor. *Aging in the 1980s: Psychological issues*. Washington, DC: American Psychological Association; 1980. p. 332-340.
- Christensen CA, Ford JM, Pfefferbaum A. The effect of stimulus-response incompatibility on P3 latency depends on the task but not on age. *Biological Psychology*. 1996; 44:121–141. [PubMed: 8913525]
- Coles MGH. Modern mind-brain reading. *Psychophysiology*. 1989; 26:251–269. [PubMed: 2667018]
- DeJong R, Liang CC, Lauber E. Conditional and unconditional automaticity: A dual-process model of effects of spatial stimulus-response correspondence. *Journal of Experimental Psychology: Human Perception and Performance*. 1994; 20:731–750. [PubMed: 8083631]
- DeJong R, Wierda M, Mulder G, Mulder LJM. The use of partial information in response preparation. *Journal of Experimental Psychology: Human Perception & Performance*. 1988; 14:682–692. [PubMed: 2974876]
- Dien J, Spencer KM, Donchin E. Parsing the late positive complex: Mental chronometry and the ERP components that inhabit the neighborhood of the P300. *Psychophysiology*. 2004; 41:665–678. [PubMed: 15318873]
- Donders FC. On the speed of mental processes. *Acta Psychologica*. 1868–1869; 1969; 30:412–431. [PubMed: 5811531]
- Eimer M. The lateralized readiness potential as an on-line measure of central response activation processes. *Behavior Research Methods, Instrument, & Computers*. 1998; 30:146–156.
- Eriksen BA, Eriksen CW. Effects of noise letters upon the identification of a target letter in a nonsearch task. *Perception & Psychophysics*. 1974; 16:143–149.
- Falkenstein M, Hohnsbein J, Hoorman J. Late visual and auditory ERP components and choice reaction time. *Biological Psychology*. 1993; 35:201–224. [PubMed: 8218614]

- Falkenstein M, Hohnsbein J, Hoorman J. Effects of choice complexity on different subcomponents of the late positive complex of the event-related potential. *Electroencephalography and Clinical Neurophysiology*. 1994; 92:148–160. [PubMed: 7511512]
- Falkenstein M, Yordanova J, Kolev V. Effects of aging on slowing of motor-response generation. *International Journal of Psychophysiology*. 2006; 59:22–29. [PubMed: 16257076]
- Farwell LA, Martinerie JM, Bashore TR, Rapp PE, Goddard PH. Optimal digital filters for long latency components of the event-related brain potential. *Psychophysiology*. 1993; 30:306–315. [PubMed: 8497560]
- Fisher, DL.; Duffy, SA.; Katsikopoulos, KV. Cognitive slowing among older adults: What kind and how much?. In: Perfect, TJ.; Maylor, EA., editors. *Models of cognitive aging*. New York, NY: Oxford University Press; 2000. p. 87-124.
- Fisher, DL.; Fisk, AD.; Duffy, SA. Why latent models are needed to test hypotheses about the slowing of word and language processes in older adults. In: Allen, PA.; Bashore, TR., editors. *Age differences in word and language processing*. Amsterdam: Elsevier Science; 1995. p. 1-29.
- Fisk AD, Fisher DL. Brinley plots and theories of aging: The explicit, muddled and implicit debates. *Journal of Gerontology: Psychological Sciences*. 1994; 49:P81–89.
- Fisk AD, Fisher DL, Rogers WA. General slowing cannot explain age-related search effects: Reply to Cerella (1991). *Journal of Experimental Psychology: General*. 1992; 121:73–78. [PubMed: 1534348]
- Fjell AM, Rosquist H, Walhovd KB. Instability in the latency of P3a/P3b potentials and cognitive function in aging. *Neurobiology of Aging*. 2009; 30:2065–2079. [PubMed: 18339453]
- Ford JM, Pfefferbaum A, Tinklenberg JR, Kopell BS. Effects of perceptual and cognitive difficulty on P3 and RT in young and old adults. *Electroencephalography and Clinical Neurophysiology*. 1982; 54:311–321. [PubMed: 6179758]
- Ford JM, Roth WT, Mohs RC, Hopkins WF, Kopell BS. Event-related potentials recorded from young and old adults during a memory retrieval task. *Electroencephalography and Clinical Neurophysiology*. 1979; 47:450–459. [PubMed: 89949]
- Geary DC, Wiley JG. Cognitive addition: Strategy choice and speed-of-processing differences in young and elderly adults. *Psychology and Aging*. 1991; 6:474–483. [PubMed: 1930764]
- Goodin DS, Squires KC, Henderson BH, Starr A. Age-related variations in evoked potentials to auditory stimuli in normal human subjects. *Electroencephalography and Clinical Neurophysiology*. 1978; 44:447–458. [PubMed: 76553]
- Gratton G, Coles MGH, Donchin E. A new method for off-line removal of ocular artifact. *Electroencephalography and Clinical Neurophysiology*. 1983; 55:468–484. [PubMed: 6187540]
- Gratton G, Coles MGH, Sirevaag ET, Eriksen CW, Donchin E. Pre- and post-stimulus activation of response channels: A psychophysiological analysis. *Journal of Experimental Psychology: Human Perception & Performance*. 1988; 14:331–344. [PubMed: 2971764]
- Greenwood PM, Parasuraman R, Haxby JV. Changes in visuospatial attention over the adult lifespan. *Neuropsychologia*. 1993; 31:471–485. [PubMed: 8502379]
- Hackley SA, Miller J. Response complexity and precue interval effects on the lateralized readiness potential. *Psychophysiology*. 1995; 32:230–241. [PubMed: 7784531]
- Hale S, Lima SD, Myerson J. General cognitive slowing in the nonlexical domain: An experimental validation. *Psychology and Aging*. 1991; 6:512–521. [PubMed: 1777138]
- Hartley AA. Evidence for selective preservation of spatial selective attention in old age. *Psychology and Aging*. 1993; 8:371–379. [PubMed: 8216957]
- Hartley AA. Age differences in dual-task interference are localized to response-generation processes. *Psychology and Aging*. 2001; 16:47–54. [PubMed: 11302367]
- Hartley AA, Kieley JM. Adult age differences in the inhibition of return of visual attention. *Psychology and Aging*. 1995; 10:670–683. [PubMed: 8749594]
- Hartley AA, Kieley JM, McKenzie CRM. Allocation of visual attention in younger and older adults. *Perception and Psychophysics*. 1992; 52:175–185. [PubMed: 1508625]
- Hartley AA, Kieley JM, Slabach EH. Age differences and similarities in the effects of cues and prompts. *Journal of Experimental Psychology: Human Perception and Performance*. 1990; 16:523–537. [PubMed: 2144568]

- Hartley AA, Little DM. Age-related differences and similarities in dual-task interference. *Journal of Experimental Psychology: General*. 1999; 128:416–449. [PubMed: 10650582]
- Hartley AA, Maquestiaux F. Success and failure at dual-task coordination by younger and older adults. *Psychology and Aging*. 2007; 22:215–222. [PubMed: 17563177]
- Heffley EF, Foote B, Mui T, Donchin E. Pearl II: Portable laboratory computer system for psychophysiological assessment using event related brain potentials. *Neurobehavioral Toxicology and Teratology*. 1985; 7:399–407. [PubMed: 3840578]
- Hohnsbein J, Falkenstein M, Hoorsman J. Effects of attentional and time-pressure on P300 subcomponents and implications for mental workload research. *Biological Psychology*. 1995; 40:73–81. [PubMed: 7647187]
- Hohnsbein J, Falkenstein M, Hoorsman J, Blanke L. Effects of crossmodal divided attention on late ERP components. I. Simple and choice reaction tasks. *Electroencephalography and Clinical Neurophysiology*. 1991; 78:438–446. [PubMed: 1712279]
- Howard DV. The effects of aging and degree of association on the semantic priming of lexical decisions. *Experimental Aging Research*. 1983; 9:145–151. [PubMed: 6641773]
- Jasper HH. The ten-twenty electrode system of the International Federation. *Electroencephalography and Clinical Neurophysiology*. 1958; 10:371–375.
- Kok A. Age-related changes in involuntary and voluntary attention as reflected in components of the event-related potential (ERP). *Biological Psychology*. 2000; 54:107–143. [PubMed: 11035221]
- Kubo-Kawai N, Kawai N. Elimination of the enhanced Simon effect for older adults in a three-choice situation: Ageing and the Simon effect in a go/no-go Simon task. *The Quarterly Journal of Experimental Psychology*. 2010; 63:452–464. [PubMed: 19575334]
- Kutas M, McCarthy G, Donchin E. Augmenting mental chronometry: The P300 as a measure of stimulus evaluation time. *Science*. 1977; 197:792–795. [PubMed: 887923]
- Leuthold H, Jentzsch I. Distinguishing neural sources of movement preparation and execution—An electrophysiological analysis. *Biological Psychology*. 2002; 60:173–198. [PubMed: 12270590]
- Lima SD, Hale S, Myerson J. How general is general slowing? Evidence from the lexical domain. *Psychology and Aging*. 1991; 6:416–425. [PubMed: 1930758]
- Little DM, Hartley AA. Further evidence that negative priming in the Stroop color-word task is equivalent in older and younger adults. *Psychology and Aging*. 2000; 6:416–425.
- Looren de Jong H, Kok A, Van Rooy JCGM. Early and late selection in young and old adults: An event-related potential study. *Psychophysiology*. 1988; 25:657–671. [PubMed: 3241853]
- Madden DJ. Four to ten milliseconds per year: Age-related slowing of visual word identification. *Journal of Gerontology: Psychological Sciences*. 1992; 47:P59–P68.
- Madden DJ, Langley LK. Age-related changes in selective attention and perceptual load during visual search. *Psychology and Aging*. 2003; 18:54–67. [PubMed: 12641312]
- Madden DJ, Pierce TW, Allen PA. Age-related slowing and the time course of semantic priming in visual word recognition. *Psychology and Aging*. 1993; 8:490–507. [PubMed: 8292278]
- Madden DJ, Pierce TW, Allen PA. Adult age differences in the use of distractor homogeneity during visual search. *Psychology and Aging*. 1996; 11:454–474. [PubMed: 8893315]
- Madden DJ, Turkington TG, Provenzale JM, Denny LL, Langley LK, Hawk TC, Coleman RE. Aging and attentional guidance during visual search: Functional neuroanatomy by positron emission tomography. *Psychology and Aging*. 2002; 17:24–43. [PubMed: 11931285]
- Madden DJ, Welsh-Bohmer KA, Tupler LA. Task complexity and signal detection analyses of lexical decision performance in Alzheimer's disease. *Developmental Neuropsychology*. 1999; 16:1–18.
- Magen H, Cohen A. Modularity beyond perception: Evidence from single task interference paradigms. *Cognitive Psychology*. 2007; 55:1–36. [PubMed: 17083928]
- Magliero A, Bashore TR, Coles MGH, Donchin E. On the dependence of P300 latency on stimulus evaluation processes. *Psychophysiology*. 1984; 21:171–186. [PubMed: 6728983]
- Masaki H, Wild-Wall N, Sangals J, Sommer W. The functional locus of the lateralized readiness potential. *Psychophysiology*. 2004; 41:220–230. [PubMed: 15032987]
- Maylor EA, Lavie N. The influence of perceptual load on age differences in selective attention. *Psychology and Aging*. 1998; 13:563–573. [PubMed: 9883457]

- McCarthy G, Donchin E. A metric for thought: A comparison of P300 latency and reaction time. *Science*. 1981; 211:77–80. [PubMed: 7444452]
- Miller J. The flanker compatibility effect as a function of visual angle, attentional focus, visual transients, and perceptual load: A search for boundary conditions. *Perception & Psychophysics*. 1991; 49:270–288. [PubMed: 2011464]
- Miller J, Coles MGH, Chakraborty S. Dissociation between behavioral and psychophysiological measures of response preparation. *Acta Psychologica*. 1996; 94:189–208. [PubMed: 8942313]
- Myerson, J.; Hale, S. General slowing and age invariance in cognitive aging: The other side of the coin. In: Cerella, J.; Rybash, J.; Hoyer, W.; Commons, ML., editors. *Adult information processing: Limits on loss*. San Diego, CA: Academic Press; 1993. p. 115-141.
- O'Connell RG, Dockree PM, Kelly SP. A supramodal accumulation-to-bound signal that determines perceptual decisions in humans. *Nature Neuroscience*. 2012; 15:1729–1735. [PubMed: 23103963]
- Osman A, Bashore TR, Coles MGH, Donchin E, Meyer DE. On the transmission of partial information: Inferences from movement-related brain potentials. *Journal of Experimental Psychology: Human Perception and Performance*. 1992; 18:217–232. [PubMed: 1532189]
- Osman A, Moore CM. The locus of dual-task interference: Psychological refractory effects on movement-related brain potentials. *Journal of Experimental Psychology: Human Perception and Performance*. 1993; 19:1292–1312. [PubMed: 8294893]
- Osman A, Moore CM, Ulrich R. Bisecting RT with lateralized readiness potentials: Precue effects after LRP onset. *Acta Psychologica*. 1995; 90:111–127. [PubMed: 8525867]
- Perfect TJ. What can Brinley plots tell us about cognitive aging? *Journal of Gerontology: Psychological Sciences*. 1994; 49:P60–64.
- Perfect, TJ.; Maylor, EA., editors. *Theoretical debate in cognitive aging*. Oxford: Oxford University Press; 2000.
- Pfefferbaum A, Christensen C, Ford JM, Kopell BS. Apparent response incompatibility effects on P3 latency depend on the task. *Electroencephalography and Clinical Neurophysiology*. 1986; 64:424–437. [PubMed: 2428593]
- Pfefferbaum A, Ford JM. ERPs to stimuli requiring response production and inhibition: effects of age, probability and visual noise. *Electroencephalography and Clinical Neurophysiology*. 1988; 71:55–63. [PubMed: 2446846]
- Pfefferbaum A, Ford JM, Roth WT, Kopell BS. Age differences in P3-reaction time associations. *Electroencephalography and Clinical Neurophysiology*. 1980; 49:257–265. [PubMed: 6158402]
- Possamai CA, Bule B, Osman A, Harbroucq T. Partial advance information, number of alternatives, and motor processes: An electromyographic study. *Acta Psychologica*. 2002; 111:124–139.
- Pratt HJ, Michalewski HJ, Patterson JV, Starr A. Brain potentials in a memory-scanning task. II. Effects of aging on potentials to the probes. *Electroencephalography and Clinical Neurophysiology*. 1989; 72:507–517. [PubMed: 2471620]
- Proctor RW, Pick DF, Vu KPL, Anderson RE. The enhanced Simon effect for older adults is reduced when the irrelevant location information is conveyed by an accessory stimulus. *Acta Psychologica*. 2005; 119:21–40. [PubMed: 15823241]
- Proctor, RW.; Vu, K-PL. *Stimulus–response compatibility principles. Data, theory, and application*. Boca Raton, FL: CRC Press; 2006.
- Ragot R. Perceptual and motor space representation: An event related potential study. *Psychophysiology*. 1984; 21:159–170. [PubMed: 6728982]
- Ragot, R. Cerebral evoked potentials: Early indexes of compatibility effects. In: Proctor, RW.; Reeve, TG., editors. *Stimulus-response compatibility: An integrated approach*. Amsterdam: North-Holland; 1990. p. 225-239.
- Ragot R, Lesevre N. Electrophysiological study of intrahemispheric compatibility effects elicited by visual directional cues. *Psychophysiology*. 1986; 23:19–27. [PubMed: 3945704]
- Ragot R, Renault B. P300 as a function of S-R compatibility and motor programming. *Biological Psychology*. 1981; 13:289–294. [PubMed: 7342999]
- Ragot R, Renault B. P300 and S-R compatibility: A reply to Magliero et al. *Psychophysiology*. 1985; 22:349–352. [PubMed: 4011807]

- Ratcliff R, Spieler D, McKoon G. Explicitly modeling the effects of aging on response time. *Psychonomic Bulletin & Review*. 2000; 7:1–25. [PubMed: 10780018]
- Ratcliff R, Thapar A, McKoon G. The effects of aging on reaction time in a signal detection task. *Psychology and Aging*. 2001; 16:323–341. [PubMed: 11405319]
- Requin J, Riehle A. Neural correlates of partial transmission of sensorimotor information in the cerebral cortex. *Acta Psychologica*. 1995; 90:81–95. [PubMed: 8525878]
- Ridderinkhof KR, van der Molen MW, Band GPH, Bashore TR. Sources of interference from irrelevant information: A developmental study. *Journal of Experimental Child Psychology*. 1997; 65:315–341. [PubMed: 9178963]
- Roggeveen AB, Prime DJ, Ward LM. Lateralized readiness potentials reveal motor slowing in the aging brain. *Journal of Gerontology: Psychological Sciences*. 2007; 62B:P78–P84.
- Rubichi S, Neri M, Nicoletti R. Age-related slowing of control processes: Evidence from a response coordination task. *Cortex*. 1999; 35:573–582. [PubMed: 10574082]
- Salthouse, TA. Speed of processing and its implications for cognition. In: Birren, JE.; Schaie, KW., editors. *Handbook of the psychology of aging*. New York, NY: Van Nostrand Reinhold; 1985a. p. 400–426.
- Salthouse, TA. *A theory of cognitive aging*. Amsterdam: North-Holland; 1985b.
- Sanders AF. Issues and trends in the debate on discrete vs. continuous processing of information. *Acta Psychologica*. 1990; 74:123–167.
- Sangals J, Sommer W, Leuthold H. Influences of presentation mode and time pressure on the utilisation of advance information on response preparation. *Acta Psychologica*. 2002; 109:1–24. [PubMed: 11766138]
- Satz P, Mogul S. An abbreviation of the WAIS for clinical use. *Journal of Clinical Psychology*. 1962; 18:77–79. [PubMed: 14497487]
- Simon, JR. The effects of an irrelevant directional cue on human information processing. In: Proctor, RW.; Reeve, TG., editors. *Stimulus-response compatibility*. Amsterdam: North-Holland; 1990. p. 31–86.
- Simon JR, Pouraghabagher AR. The effect of aging on the stages of processing in a choice reaction time task. *Journal of Gerontology*. 1978; 33:553–561. [PubMed: 752045]
- Sliwinski M. Aging and counting speed: Evidence for process-specific slowing. *Psychology and Aging*. 1997; 12:38–49. [PubMed: 9100267]
- Smulders FTY, Kenemans JL, Schmidt WF, Kok A. Effects of task complexity in young and old adults: Reaction time and P300 latency are not always dissociated. *Psychophysiology*. 1999; 36:118–125. [PubMed: 10098387]
- Smulders F, Kok A, Kenemans L, Bashore TR. The temporal specificity of factor effects on the reaction process revealed in ERP component latencies. *Acta Psychologica*. 1995; 90:97–109. [PubMed: 8525879]
- Spierer DH, Balota DA, Faust ME. Stroop performance in healthy younger and older adults and in individuals with dementia of the Alzheimer's type. *Journal of Experimental Psychology: Human Perception and Performance*. 1996; 22:461–479. [PubMed: 8934854]
- Sternberg, S. The discovery of processing stages: Extensions of Donders' method. In: Koster, WG., editor. *Attention and performance*. Vol. II. 1969. p. 276–315. *Acta Psychologica*. Amsterdam: North-Holland; p. 30
- Strayer DL, Wickens CD, Braune R. Adult age changes in the speed and capacity of information processing. II. An electrophysiological approach. *Psychology and Aging*. 1987; 2:99–110. [PubMed: 3268210]
- Teichner WH, Krebs MJ. Laws of choice reaction time. *Psychological Review*. 1974; 81:75–98. [PubMed: 4812881]
- Thapar A, Ratcliff R, McKoon G. A diffusion model analysis of the effects of aging on letter discrimination. *Psychology and Aging*. 2003; 18:415–429. [PubMed: 14518805]
- Treccani B, Cubelli R, Della Sala S, Umiltà C. Flanker and Simon effects interact at the response selection stage. *The Quarterly Journal of Experimental Psychology*. 2009; 62:1784–1804. [PubMed: 19180364]

- Van Asselen M, Ridderinkhof KR. Shift costs of predictable and unexpected set shifting in young and older adults. *Psychologica Belgica*. 2001; 40:259–273.
- van der Lubbe RHJ, Verleger R. Aging and the Simon task. *Psychophysiology*. 2002; 39:100–110. [PubMed: 12206290]
- van der Molen, MW.; Bashore, TR.; Halliday, RF.; Callaway, E. Chronopsychophysiology: Mental chronometry augmented by psychophysiological time markers. In: Jennings, JR.; Coles, MGH., editors. *Handbook of cognitive psychophysiology*. New York, NY: J. Wiley & Sons; 1991. p. 9-178.
- Verhaegen, P.; Cerella, J. Everything we know about aging and response times: A meta-analytic integration. In: Hofer, SM.; Alwin, DF., editors. *Handbook of cognitive aging: Interdisciplinary perspectives*. Los Angeles, CA: Sage Publications; 2008. p. 134-150.
- Verleger R. On the utility of P3 latency as an index of mental chronometry. *Psychophysiology*. 1997; 34:131–156.
- Verleger R, Ja kowski P, Wascher E. Evidence for an integrative role of P3b in linking reaction to perception. *Journal of Psychophysiology*. 2005; 19:165–181.
- Verleger R, Neukäter W, Kompf D, Vieregge P. On the reasons for the delay of P3 latency in healthy elderly subjects. *Electroencephalography and Clinical Neurophysiology*. 1991; 79:488–502. [PubMed: 1721576]
- Vu KPL, Proctor RW. Age differences in response selection for pure and mixed stimulus–response mappings and tasks. *Acta Psychologica*. 2008; 129:49–60. [PubMed: 18541219]
- Wechsler, D. Wechsler adult intelligence scale. New York, NY: Psychological Corporation; 1955.
- Welford, AT. Skill and age: An experimental approach. London: Oxford University Press; 1951.
- Whiting WL, Madden DJ, Babcock KJ. Overriding age differences in attentional capture with top-down processing. *Psychology and Aging*. 2007; 22:223–232. [PubMed: 17563178]
- Wild-Wall N, Falkenstein M, Hohnsbein J. Flanker interference in young and older participants as reflected in event-related potentials. *Brain Research*. 2008; 1211:77–84.
- Yordanova J, Kolev V, Hohnsbein J, Falkenstein M. Sensorimotor slowing with ageing is mediated by a functional dysregulation of motor-generation processes: Evidence from high-resolution event-related potentials. *Brain*. 2004; 127:351–362. [PubMed: 14607784]
- Zeef EJ, Kok A. Age-related differences in the timing of stimulus and response processes during visual selective attention: Performance and psychophysiological analyses. *Psychophysiology*. 1993; 30:138–151. [PubMed: 8434077]
- Zeef EJ, Sonke CJ, Kok A, Buiten MM, Kenemans JL. Perceptual factors affecting age-related differences in focused attention: Performance and psychophysiological analyses. *Psychophysiology*. 1996; 33:555–565. [PubMed: 8854743]

# # # # #	R I G H T A	L Z Q R H M
L E F T # #	B D F C G E	J D W N X F
# # # # #	G A B F D C	U L E F T P
# # # # #	D B G C F A	V A B G Y E
#	A-G	A-Z

Figure 1.

Examples of #, A-G, and A-Z matrices. Note that on a trial-by-trial basis the target, LEFT or RIGHT, appeared pseudorandomly in any one of the 4 rows and in any of the appropriate starting columns.

Figure 2.

Grand average ERPs for young adults in the choice reaction. Fz is the short dashed line; Cz is the solid line; Pz is the dotted line; and Oz is the long dashed line. Matrix onset is indicated by the solid vertical line at time 0. Components are identified at the scalp site where they were largest.

Figure 3.

Factor patterns for each dependent measure (RT, P300 latency, Accuracy). *F* ratios in the lower left corner of each panel are for the analyses on mean values. The mean values for each data point are also shown. Y and O indicate, respectively, young and older adults; Cp and Ip indicate, respectively, compatible and incompatible responses; and #, A-G, and A-Z indicate the three levels of noise in the matrix surround.

Figure 4.

Grand average ERPs for the older adults in the choice reaction. Fz is the short dashed line; Cz is the solid line; Pz is the dotted line; and Oz is the long dashed line. Matrix onset is indicated by the solid vertical line at time 0. Components are identified at the scalp site where they were largest.

Figure 5.

(A) The model offered by Smulders et al. (1999) in explanation of the pattern of results they found. (B) Our proposed additions to that model. Please note that the depicted model is for young adults. As a result, the hypothesized overlap in processing between the S-R translation and response selection stages among older adults is not shown. The ?s shown under the S-R translation and Response Selection stages reflect our uncertainty about the relative influences of variations in age and S-R compatibility on these two stages of processing. Please note that the box with the dashed lines at the end of both models could very well be identified as the *motor adjustment stage* of Sanders (1990); or what Yordanova et al. (2004) referred to as the *motor response generation stage* and Falkenstein et al. (2006) called the *motor stage of sensorimotor processing*.

Table 1

Windows for estimating component latencies

	P300	Range
Young		
#	350–960	200–600 500–1300
letters	440–1080	230–650 700–1500
Older		
#	440–940	200–640 600–1500
letters	530–1160	260–800 750–1700

Note: The range of times shown in each row of the P300 column are the mean lower and upper edges of the windows used for estimating P300 latency for # and letter (both A-G and A-Z) surrounds for young and older adults. The time ranges shown in the top and bottom row of each section of the range column indicate the range of the lower (e.g., 200–600) and upper (e.g., 500–1300) edges of the latency window for the target surround.

Table 2

IQ scores

Age Group	Full Scale	Verbal	Performance
Young	124.65 (104–142)	126.00 (106–143)	119.79 (90–141)
Older	126.15 (106–143)	127.77 (103–151)	120.71 (101–144)

Note: The range is shown in parentheses below the mean value.

Table 3

Mean factor level values and costs

Young and Older Adults									
	RTcP	RTIp	CostIp	P3Cp	P3Ip	CostIp	AccCp	AccIp	CostIp
<i>Young</i>									
#	507.32	639.00	131.68	467.38	506.12	38.74	97.18	92.56	-4.62
CostN	160.27	162.29		190.65	193.65		-4.09	-1.71	
A-G	667.59	801.29	133.70	658.03	699.77	41.74	93.09	90.85	-2.24
CostN	49.23	48.15		35.41	32.05		-0.80	-1.47	
A-Z	716.82	849.44	132.62	693.44	731.82	38.38	92.29	89.38	-2.91
<i>Older</i>									
#	690.85	818.74	128.09	649.91	678.41	28.50	98.35	96.59	-0.76
CostN	221.06	239.67		190.65	184.50		-8.47	-7.41	
A-G	911.71	1058.41	146.70	840.56	862.91	22.35	89.88	89.18	-0.70
CostN	45.79	48.30		23.47	19.30		-0.85	-0.91	
A-Z	957.50	1106.71	149.21	864.03	882.21	18.18	89.03	88.27	-0.76

Note: Different levels of Noise (N) are indicated by #, A-G, and A-Z; compatible and incompatible responses are identified as Cp and Ip; RT and P300 latency values are in milliseconds and accuracy (Acc) rates are in percent correct.

Table 4

Analysis summary

Factor	df	Mean and Log(natural) Data									
		<i>F</i>		<i>p</i>		<i>MSE</i>		OP			
		Mean	Log N	Mean	Log N	Mean	Log N	Mean	Log N	Mean	Log N
<i>Age (A)</i>	1,66										
RT		38.32	40.53	<.0001	<.0001	137219.17	0.197	1.000	1.000	1.000	1.000
P300 L		17.31	18.89	<.0001	<.0001	170827.93	0.265	0.984	1.000	1.000	1.000
<i>SRC</i>	1,66										
RT		601.89	617.93	<.0001	<.0001	3180.82	0.005	1.000	1.000	1.000	1.000
P300 L		61.23	66.49	<.0001	<.0001	1633.39	0.003	1.000	1.000	1.000	1.000
<i>Noise (N)</i>	2,132										
RT		980.93	1181.97	<.0001	<.0001	2311.29	0.003	1.000	1.000	1.000	1.000
P300 L		148.74	159.84	<.0001	<.0001	12813.02	0.030	1.000	1.000	1.000	1.000
<i>SRC × Age</i>	1,66										
RT		0.602	5.30	.44	.024	3180.72	0.005	0.119	0.621	0.119	0.621
P300 L		4.31	10.84	.042	.002	1633.39	0.003	0.534	0.900	0.534	0.900
<i>Noise × Age</i>	2,132										
RT		22.86	1.03	<.0001	.360	2311.29	0.003	1.000	0.227	1.000	0.227
P300 L		0.203	2.21	.82	.11	12813.02	0.030	0.081	0.444	0.081	0.444
<i>SRC × Noise</i>	2,132										
RT		2.29	21.97	.11	<.0001	566.31	0.001	0.458	1.000	0.458	1.000
P300 L		0.404	3.31	.67	.04	633.62	0.001	0.114	0.618	0.114	0.618
<i>SRC × N × A</i>	2,132										
RT		1.74	3.16	.18	.046	566.31	0.001	0.360	0.597	0.360	0.597
P300 L		0.411	0.14	.66	.873	633.62	0.001	0.115	0.071	0.115	0.071

OP, observed power.