



Cognition and Aging: A Highly Selective Overview of Event-Related Potential (ERP) Data

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ABSTRACT

An overview of highly selected cognitive aging investigations of deviance detection, episodic memory and working memory reveals two primary themes: (1) when variability in elderly samples has been assessed, it has proven useful in understanding age-related changes in cognition; and (2) there is a frontal lobe contribution to at least some age-related changes in cognition. However, there are too few ERP age-related investigations of individual differences to determine whether the changes in patterns of ERP responding can be deemed “compensatory” or “inefficient.” It is suggested that, to the extent possible, future electrophysiological investigations of cognitive aging (as well as other physiological measurement techniques) include individual difference measures that will enable the determination of the implication of a given neural pattern in the genesis of a given, age-related behavioral outcome pattern.

INTRODUCTION

The last decade of cognitive aging research has shown convincingly that not all aspects of cognition show losses with similar trajectories as individuals age. For example, within the domain of memory function, performance on episodic tasks that require the reinstatement of the surrounding spatio- (where) and temporal- (when) context (i.e., source) of a previous event, shows large age-related decline (Spencer & Raz, 1995), whereas retrieving the content does not. Working memory (WM), the process by which information is coded into a short-term buffer, actively maintained and subsequently retrieved also shows age-related decrement (Jonides et al., 2000). On the other hand, simple, old/new recognition memory does not show as dramatic a decrement and, in some studies, shows no age-related deficit at all (Craik & McDowd, 1987).

It is also widely known that a good deal of performance variability exists within the normally aging population. Hence, the general trends suggested by the preceding paragraph do not apply to all elderly individuals. For example, it has been noted in both the behavioral (Li, Lindenberger, Freund, & Baltes, 2001) and physiological (Cabeza, Anderson, Locantore, & McIntosh, in press) literatures that some older individuals “compensate” for the deleterious effects of aging. Some have argued, based primarily on the results of recent hemodynamic imaging studies (Cabeza, 2002; Grady & Craik, 2000; see also Stern, 2002), that this neurocognitive compensation takes the form of the activation of neural networks different from those recruited by the young. This “compensation” hypothesis suggests that similar performance to that of the young is enabled by recruiting different brain regions not activated by the young. Strong

evidence for the compensation view would seem to require that elderly individuals who show the pattern in question also demonstrate better performance than those elderly subjects who do not.

Potential contributors to individual differences in performance and perhaps the recruitment of different brain networks, are educational level and socio-economic-status (SES), which are often linked in their modulating effects on cognitive task performance. For example, low levels of education have been shown to be a risk factor for the development of dementia, whereas high levels of education have been associated with better cognitive test performance in the nondemented elderly (e.g., Mayeux, Small, Tang, Tycko, & Stern, 2001; Schmand et al., 1997; Stern, Albert, Tang, & Tsai, 1999). These kinds of observations have led to the "cognitive reserve" hypothesis, that is, that education (or its surrogates, such as SES) may provide a buffer or reserve capacity for the deleterious effects of aging on brain function (see Stern, 2002 for a review). This hypothesis predicts that, in the normally aging adult, greater levels of education should be associated with greater changes in brain structure and function (Coffey, Saxton, Ratcliff, Bryan, & Lucke, 1999). This kind of result has been reported by (Coffey et al., 1999), who showed that, in the nondemented elderly, higher levels of educational attainment were associated with greater degrees of cerebral atrophy. Because of limitations inherent in all cross-sectional designs, this finding requires replication. Nevertheless, it is an intriguing result that might help explain some of the age-related differences in electrical activity observed at the scalp, as well as age-related changes observed in fMRI investigations of cognitive aging (Anderson & Grady, 2001).

A continually expanding literature implicates age-related change in frontal lobe processing in the etiology of cognitive aging phenomena, including performance decrements on episodic memory, working memory, and novelty detection tasks (for review, see West, 2001; but, see Greenwood, 2000 for a contrasting view). This "frontal lobe deficit hypothesis" was first articulated by Albert and Kaplan (1980), and receives support from a wide variety of research domains, including structural and functional neuroimaging,

performance on standard neuropsychological tests presumed to tap the integrity of the frontal cortex (see Mountain & Snow, 1993 and Salthouse, Fristoe, & Rhee, 1996 for caveats), and performance decrements on experimental tasks on which patients with circumscribed frontal lobe lesions perform poorly (see Friedman, 2000 for a review).

Frontal lobe deficits might be implicated in age-related compensation. For example, an interpretation we have advanced for age-related change in tasks requiring the detection of deviance (Fabiani & Friedman, 1995; Friedman, Cycowicz, & Gaeta, 2001) suggests that older adults compensate for compromised frontal lobe function by continually recruiting prefrontal cortex to encode, store and retrieve information, even after long experience with the stimuli. For younger adults, after minimal exposure to these stimuli, prefrontal contributions are no longer required.

The recruitment of frontal cortex also appears to be required for more traditional memory tasks. For example, both episodic memory and working memory require strategic or executive processes (which are initiated in prefrontal cortex), as both necessitate the management (i.e., selection and organization) of information that is retrieved from more posterior cortical areas. These posterior regions are considered to be the repository of, for example, contextual aspects of initial learning in the case of episodic memory, and modality specific information (e.g., visual, auditory) for working memory. Neuropsychological as well as functional neuroimaging data have provided compelling evidence that the prefrontal cortex is a critical element in both the retrieval of source information during episodic memory tasks (Cabeza et al., 1997) and the maintenance and selection of information on line during working memory tasks (Rowe, Toni, Josephs, Frackowiak, & Passingham, 2000). Another functional neuroimaging technique, the event-related brain potential (ERP), has also been used in the assessment of episodic (Wilding, 2001) and working (McEvoy, Smith, & Gevins, 1998) memory. Although it is difficult to infer the intracranial source of ERP activity simply from inspection of the potentials recorded on the scalp,

this technique has also yielded evidence consistent with prefrontal cortical contributions to both source retrieval (Friedman & Johnson, 2000; Wilding & Rugg, 1996) and working memory (Nielsen-Bohlman & Knight, 1999). Here too, the limited evidence suggests age-related decrement in the ERP correlates of source retrieval (Trott, Friedman, Ritter, Fabiani, & Snodgrass, 1999; Wegesin, Friedman, Varughese, & Stern, 2002; but see Mark & Rugg, 1998) and working memory (Gaeta, Friedman, & Hurlie, submitted; McEvoy, Pellouchoud, Smith, & Gevins, 2001).

An important goal of cognitive aging research, as assessed by ERP methods (and other neurophysiological techniques), will be to understand which variables underlie the relationship between ERP parameters and cognitive function. Based on the frontal lobe deficit hypothesis, a potential contributing factor could be the extent of performance decrement on tests that putatively assess the integrity of prefrontal cortex. In fact, in two behavioral studies, Glisky, Polster, and Routhieaux (1995) and Glisky, Rubin, and Davidson (2001) have demonstrated that lowered performance on "frontal lobe" tests can explain a large percentage of the variance in individual differences of older adults on performance in source memory paradigms. This technique has not been employed to the same extent with physiological measures.

In the current paper, a highly selective review of age-related studies from this laboratory is undertaken. As a whole, the results of these investigations suggest that there are differences in physiological parameters of elderly participants, as manifested in ERP patterns, that may help explain age-related performance differences. For one of these studies, we have examined individual differences in education and SES (Fabiani, Friedman, Cheng, Wee, & Trott, 1999), while in another we have assessed individual differences in performance on "frontal lobe" tests (Fabiani, Friedman, & Cheng, 1998). In other investigations, including working memory (Gaeta et al., submitted), and deviance detection (Fabiani & Friedman, 1995), the ERP data are consistent with older individuals continuing to employ frontal lobe processes for dealing with repetitive stimuli which should no longer require such extensive

processing. In an investigation of encoding for subsequent episodic memory testing (Friedman & Trott, 2000), the ERP topographic data are consistent with the elderly using different neural networks to perform the task. To anticipate my conclusions, some of these patterns may be "compensatory," while others may be "inefficient," but it is too early at the current state of knowledge, at least with ERP measures, to conclude that this is the only way of explaining the neurophysiological patterns that underlie the changes in cognition that are seen with increasing age.

STUDIES OF THE "ODDBALL" PARADIGM

The purpose of using the oddball paradigm in studies of cognitive aging is to assess the brain's response to infrequently occurring, deviant stimuli (hence the label, oddball), as the detection of biologically significant events is an extremely critical cognitive function necessary for navigating everyday life. In this task, participants typically listen to two types of sounds or tones, a frequently occurring standard (e.g., 90% occurrence) and an infrequently occurring deviant or target (10% occurrence), and must respond, usually by button press, to the deviant event. The deviant event elicits a large-amplitude ERP component labeled the P3, the P300 or P3b. P3b is typically elicited by events that are considered task-relevant, or by events that require a decision (Sutton, Braren, Zubin, & John, 1965). Based on a number of converging sources of evidence, including studies of patients with brain lesions (Knight, 1990), intracranial ERP investigations (Halgren, Marinkovic, & Chauvel, 1998), hemodynamic studies (Opitz, Mecklinger, Von Cramon, & Kruggel, 1999), and scalp-recorded and magnetic ERP investigations (reviewed by Friedman et al., 2001), the P3 elicited on the scalp by auditory stimuli receives contributions from a number of brain regions, including, but not limited to, the prefrontal cortex, the temporo-parietal junction, and primary auditory cortex.

In one age-related study of the P3 component, Fabiani and Friedman (1995) presented

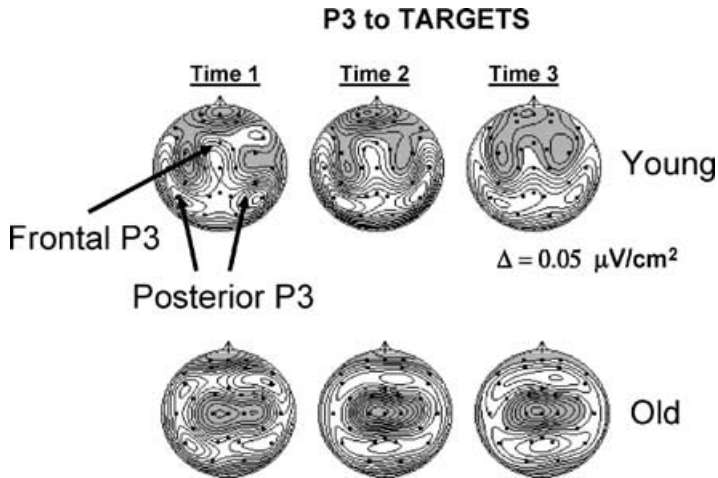


Fig. 1. Current source density (CSD) scalp distributions based on the grand mean target ERPs for 16 young (top) and 16 old (bottom) participants during three sequential “oddball” tasks. The first was a practice block (Time 1), the second a standard oddball series constructed identically to the practice block (Time 2), and the third a novelty oddball task (Time 3). The P3 was computed as the averaged voltage between 285 and 385 ms poststimulus for both groups of subjects, and the CSDs were based on that averaged voltage. Note that, for the young, the frontal P3 diminishes with time, whereas the posterior P3 remains relatively constant. For the old, by contrast, there is no such change in the frontal distribution. The Δ refers to the separation (in $\mu\text{V}/\text{cm}^2$) between isopotential lines. Small filled squares represent the recording sites. The shaded areas reflect negative activity, the unshaded areas, positive activity. Note that the maps depicted here are based on the data of eight additional subjects in each age group recruited after the publication of the Fabiani and Friedman (1995) paper.

sequentially a series of three oddball tasks. The first was a regular oddball task consisting of standards and targets, and served as the practice block of trials. The second, also a regular oddball task, was identical to the practice series. The final series comprised the novelty oddball, in which standard and deviant tones and equally infrequent “novel” environmental sounds¹ occurred. Although the participants were undoubtedly familiar with tonal stimuli, the context in which these were presented, in a “new” laboratory environment embedded within an unfamiliar oddball task, would serve to make even these tonal stimuli “novel,” especially in the first practice block. The current source density (CSD) maps of

P3 activity that resulted are depicted in Figure 1.² Note that there are two distinct aspects of the P3 elicited by the targets, one that is frontally

²Two types of maps can be generated, raw voltage (labeled surface potential, or SP) and current source density (CSD). Both SP and CSD maps are derived directly from the original amplitude data, but each provides a different view of brain activity (see Picton et al. (1995) for a complete description). During any given temporal window, scalp-recorded ERP voltages or amplitudes, the SP activity, reflect the summation of both cortical and subcortical neural activity. CSD maps, by contrast, reflect primarily cortical surface activity, because the amplitudes are spatially filtered with an algorithm that removes electrical activity that is volume conducted from subcortical areas as well as cortical areas distal to the recording electrode(s). This results in a spatially sharpened, reference-free display of positive and negative activity that emphasizes cortical differences. In the figures depicted below, when the SP and CSD maps yielded similar distributions (indicating that the data reflected primarily cortically generated activity), the SP maps are depicted; when they did not, the CSD maps are depicted.

¹The novel events were comprised of bird calls and animal sounds (e.g., mosquito, whale, frog, etc.), “noises” of various kinds (e.g., water dripping, drill, car, etc.), musical instrument sounds, human body sounds (e.g., kiss, hiccups, etc.), and artificial sounds such as those heard in video games and cartoons.

focused around the scalp midline, and the other that shows bilateral parietal foci. For the young, with time on task, there is a change in the scalp distribution of the P3, from frontally to parietally oriented, that is, there is a diminution in the frontal aspect of the distribution with no apparent change in the posterior aspect. By contrast, no such change is evident in the maps of P3 activity for the older participants; frontal activity remains constant throughout the three time periods.

The older adults performed as well as the younger adults during this target detection task. Therefore, consistent with previous data based on hemodynamic studies (e.g., Cabeza, 2002), the presence of frontal P3 activity throughout the three time periods for the older adults could be interpreted as reflecting brain activity that might be considered "compensatory." Although speculative with respect to the current data, there is evidence that, with increased time on task, prefrontal cortex contributes less to task performance and more posterior regions predominate (Pauli et al., 1994; Raichle et al., 1994). Hence, one way of interpreting these data is that prefrontal cortex activation (putatively reflected by the frontal scalp focus of the P3 during the practice block) occurs when the processes necessary for task performance have not yet been automated, with more practiced processing resulting in a reduction in prefrontal cortical activity. A complimentary interpretation that receives some support (Friedman et al., 2001) is that the frontal aspect of the target P3 reflects a representation held in working memory, which, for the older adults, has to be continually consulted in order to perform the task. On the basis of either of these views, older adults would have had to continually recruit prefrontal cortex in order to maintain good levels of performance. However, the typical oddball task is relatively easy, and performance in elderly volunteers is usually near ceiling; hence, this hypothesis cannot be tested using the accuracy of oddball performance. Nevertheless, one way to determine if this notion has some validity would be to demonstrate that the scalp distribution of the P3 component differs systematically in elderly participants who can be categorized in terms of other performance measures.

Fabiani, Friedman et al. (1998) addressed this issue by determining if elderly subjects with target P3 scalp topographies that were either frontally or parietally focused differed systematically in terms of their performance on neuropsychological tests that are presumed to reflect aspects of frontal lobe function. Measures of frontal lobe function were employed because of our keen interest in testing the frontal lobe deficit hypothesis of cognitive aging. Fabiani and colleagues (1998) found that, by contrast with the young adults, older adults showed a good deal of variability in the location on the scalp at which their target P3s were largest. Using a bootstrapping method (for complete details of this technique see Fabiani, Gratton, Corballis, Cheng, & Friedman, 1998), these investigators showed that of the 16 elderly subjects, five had reliable frontal maximal target P3 responses whereas the remaining 11 had reliable parietal-maximal target P3s. These data are depicted in Figure 2. The top row of Figure 2 depicts the ERP waveforms averaged across the five subjects in the frontal-maximal group ("old frontal"), the 11 subjects in the parietal-maximal group ("old parietal"), and the 16 young adult participants. The bottom row of the figure depicts the scalp distributions of the target P3 below the waveforms of each of the three groups of subjects. Note the distinctly different maxima of the target P3s in the two elderly groups, with the distribution of the old parietal group looking more like that of the young adult group compared to the scalp distribution of the old frontal group.

Having demonstrated the reliability of the differences in scalp distribution using the bootstrapping method, Fabiani, Friedman et al. (1998) then determined whether the two groups of older participants could be differentiated on the basis of their performance on putative tests of frontal lobe function. Based on the hypothesis that continually recruiting frontal cortex for simple stimuli that should have been easily encoded into working memory is an "inefficient" processing method, Fabiani and colleagues had predicted that those older subjects who produced more frontally-oriented target P3 responses would be relatively more impaired on tests of frontal function. As can be observed in Figure 3, this predication was

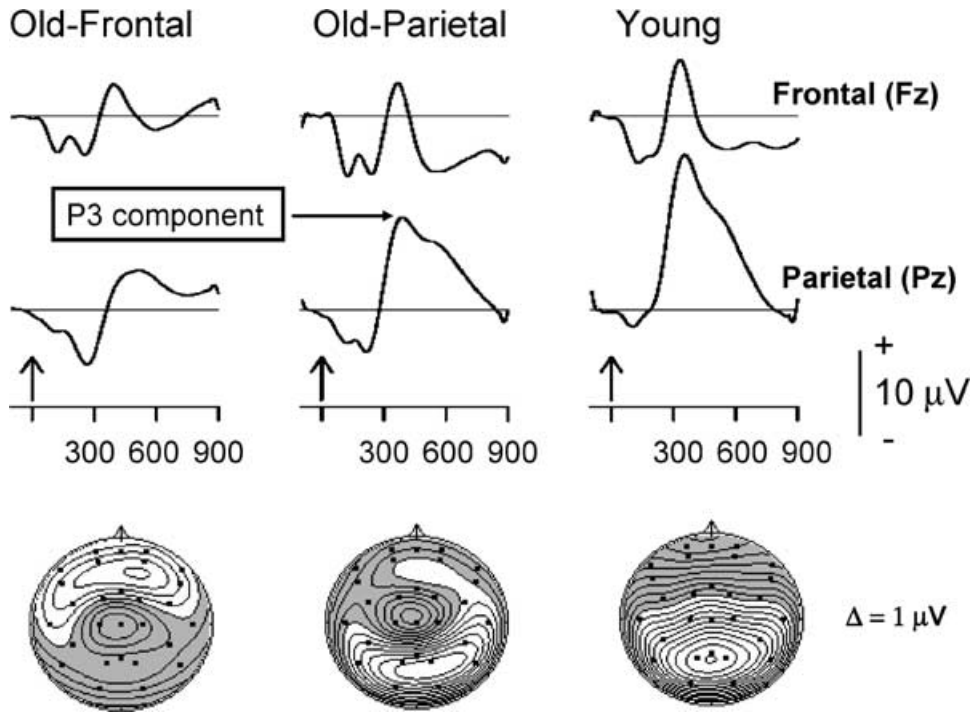


Fig. 2. Grand mean ERPs (top two rows) elicited by target events in two different groups of elderly participants. Arrows mark stimulus onset. The *Old Frontal* group ($N = 5$) is comprised of subjects whose target P3s showed frontal maxima on the majority of trials. The *Old Parietal* group ($N = 11$) is comprised of volunteers whose target P3s showed parietal maxima on the majority of trials. All subjects in the young group consistently demonstrated parietal-maximal target P3 responses. Depicted below the waveforms are the scalp distributions (based on the surface potential or SP data), of the target P3 computed on the averaged voltage between 300 and 400 ms. Note the clear distinction in the scalp distributions of the two groups of elderly subjects. The Δ refers to the separation (in μV) between isopotential lines. Small filled squares represent the recording sites. The shaded areas reflect negative activity, the unshaded areas, positive activity. Modified from (Fabiani, Friedman et al., 1998).

borne out. Although both groups of older adults performed at a lower level compared to the young adults, the group with frontal-maximal P3 potentials performed significantly more poorly than both the young adults and the old-parietal group on most measures of Wisconsin Card Sorting Test (WCST) performance. The old-frontal group did not, however, differ from the old-parietal group on a measure of general cognitive function, the Modified Mini-Mental Status Exam (Mayeux, Stern, Rosen, & Leventhal, 1981), on verbal and performance IQs, digit span, years of education or socio-economic status. These data suggest some degree of specificity with respect to the impairment on frontal lobe measures and not simply a generalized pattern of deficit.

The results of the Fabiani, Friedman et al. (1998) investigation add to the literature on the existence of individual differences in the elderly population that may have behavioral consequences (e.g., Glisky et al., 2001). The results suggest the speculation that those older individuals who have poorer frontal lobe function compensate for this deficit by continually engaging frontal cortex in order to maintain representations on line, and hence perform adequately on the task in question. These subjects may continually recruit frontal cortex, as suggested by Fabiani, Friedman et al. (1998), due to faster memory decay, reduced working memory capacity, and/or higher susceptibility to distraction.

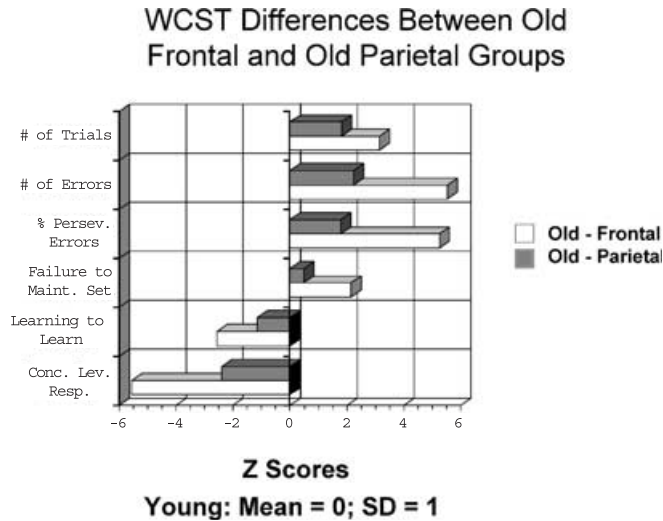


Fig. 3. Performance measures from the Wisconsin Card Sorting Test (WCST) for both the old-frontal and old-parietal subgroups of older adults. The scores of the two groups of elderly participants are plotted as a function of their deviation (z transform) from the scores of the young subjects. # of trials = total number of trials to complete the test; # of errors = total number of errors; % persever. errors = percent perseverative errors; failure to maint. set = failure to maintain set (i.e., number of times in which the subject makes at least five correct responses in a row but fails to get the 10 required to complete the category); learning to learn = a positive score indicates improved efficiency across successive categories; conc. lev. resp. = Percent conceptual level responses (i.e., runs of three or more correct responses divided by the total number of trials times 100). Modified from (Fabiani, Friedman et al., 1998).

I turn next to a consideration of recognition and working memory tasks where it also appears that some individuals in the older population may compensate for the adverse effects of aging on neurocognition by activating frontal cortex more than their poorer performing counterparts.

STUDIES OF EPISODIC MEMORY

Recognition Memory

As mentioned in the Introduction section, a voluminous cognitive aging literature demonstrates consistent age-related differences in memory performance that requires the retrieval of source information compared to the retrieval of content or item information (Spencer & Raz, 1995; see also Friedman, 2000). In two studies, we sought to determine if the difficulty arose during encoding (Friedman & Trott, 2000) or retrieval (Trott et al., 1999). A recent re-analysis of these data suggests that encoding decrements contribute more to the age-related decline in source memory than do

retrieval decrements (Friedman, 2002). For this study, we modified a recognition memory task that had been used previously to assess age-related changes in episodic memory (Howard, Heisey, & Shaw, 1986). Verbal items were presented in sentences, each with two unassociated nouns. There were two lists of sentences presented during each study cycle, and subjects were asked to memorize the nouns and the list within which they were presented. No other encoding instructions were given. We used this kind of temporal context as data from this (Fabiani & Friedman, 1997) and other laboratories (Spencer & Raz, 1995) suggests a greater age-related deficit in this kind of source memory than in other, more perceptual types of source memory (e.g., gender of voice). The retrieval data will not be discussed here (for a complete description of the methodological details and the retrieval results, see Trott et al., 1999). Following the study phase, all of the old nouns were re-presented, along with an equal number of foils, and participants were required to make old/new

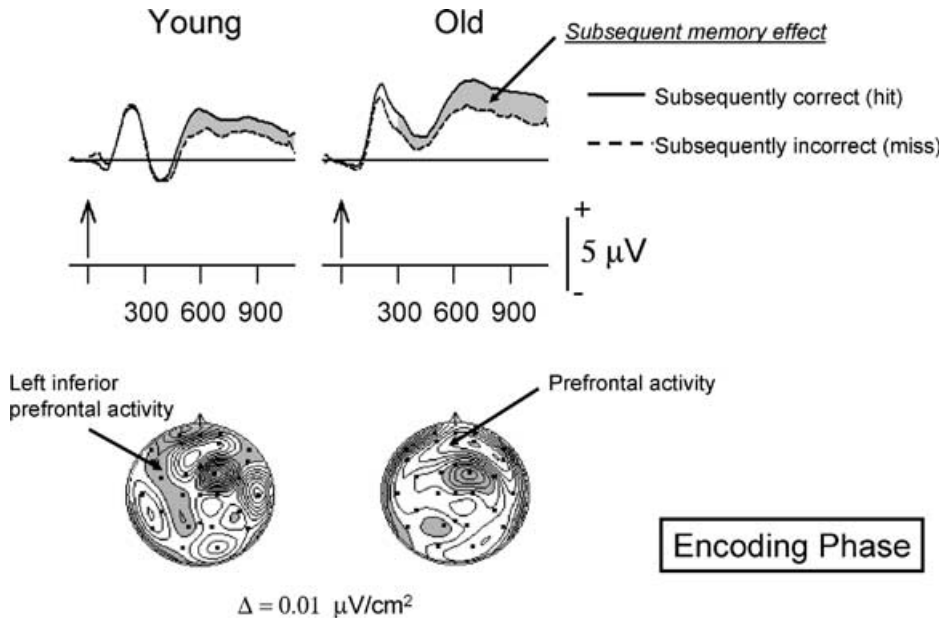


Fig. 4. Grand mean ERPs elicited by study nouns that were subsequently correctly recognized (i.e., hits) or subsequently unrecognized (i.e., misses) during the test phase in a group of 16 young and 16 older participants. The difference between these two waveforms (in gray shading) is labeled the subsequent memory effect. Arrows mark stimulus onset. The ERPs were recorded at a midline central scalp site (Cz). Depicted below the waveforms are the CSD scalp distributions corresponding to the difference between the two depicted waveforms for a period from 710 to 800 ms. The Δ refers to the separation (in $\mu\text{V}/\text{cm}^2$) between isopotential lines. Small filled squares represent the recording sites. The shaded areas reflect negative activity, the unshaded areas, positive activity.

judgments via speeded and accurate reaction time (RT). In this task, the elderly had a mean hit rate of 66%, whereas the young showed a mean hit rate of 72%. This was not a reliable difference. However, when corrected measures of recognition were computed ($\text{Pr} = \text{percent hits} - \text{percent false alarms}$; Snodgrass & Corwin, 1988), the old performed significantly more poorly than the young (mean Pr for the young = 0.63; mean Pr for the old = 0.53).

Figure 4 depicts the ERP waveforms elicited during the encoding cycles. These ERP data were evoked by nouns during the study phase and were averaged on the basis of performance during the test phase (i.e., how those particular nouns fared when they were re-presented during the test cycles). The difference between the ERPs elicited by nouns subsequently correctly recognized and those subsequently missed (the shaded areas in Fig. 4) is known as the “subsequent memory effect” (for reviews see Friedman & Johnson,

2000; Paller & Wagner, 2002). The ERP subsequent memory effect provides a measure of the encoding of the to-be-remembered item, and enables the investigator to observe the electrophysiological correlates of memory formation (Paller & Wagner, 2002). The important highlight to note about the depicted data is that, although both the young and the old show robust subsequent memory effects that begin relatively early and last for the duration of the recording epoch, the scalp distribution of this effect differs between the young and the old. For the young, the distribution is highly differentiated, showing medial frontal and bilateral posterior areas of positive activity. In addition, over left inferior prefrontal scalp (LIPS) there is a focus of negative activity. By contrast, with the exception of bilateral frontal positive foci, the scalp distribution shown by the elderly is relatively diffuse. These topographic data suggest the possibility that the young and the old engaged in qualitatively different kinds of processing when

encoding the nouns into memory. Coupled with the age-related performance difference during the retrieval phase, the topographic data suggest that the type of encoding engaged in by the elderly may have been "inefficient" relative to that recruited by the young.

On the other hand, these data may not support the notion that the difference in scalp topography reflects a compensatory mechanism, as the performance of the elderly was reliably worse than that of the young. However, it is still possible that compensatory networks were recruited, but that the compensatory activity reflected by them was not completely successful. Future investigations may be able to disentangle these alternative explanations, and two approaches based on hemodynamic data are described below (in the section headed, *One Scientist's Compensation is Another's Inefficiency*).

Nevertheless, these ERP data do appear to be consistent with recent hemodynamic studies of encoding and cognitive aging. Investigations with young adults as subjects have localized semantic or elaborative encoding to left inferior prefrontal cortex (LIPC; Demb et al., 1995; Wagner, 2002). Moreover, the results of hemodynamic studies of subsequent memory effects generally indicate that left inferior prefrontal cortex is activated to a greater extent for items that are subsequently remembered, possibly because this brain region is usually recruited when items are retrieved from semantic memory, whether during semantic retrieval tasks per se or during encoding phases for subsequent recognition memory testing (e.g., Henson, Rugg, Shallice, Josephs, & Dolan, 1999; Wagner et al., 1998). Hence, based on the absence of left inferior prefrontal scalp activity in the data of the older adults (Fig. 4), one potential contributing factor to the age-related memory deficit described here may be a failure, on the part of the older adults, in spontaneous "elaborate" or "deep" encoding (in the Friedman & Trott, 2000 study encoding strategies were self-initiated), a deficit that has been well documented from a behavioral perspective (Hashtroudi, Parker, Luis, & Reisen, 1989). Presumably, semantic or elaborative processing engenders a richly encoded memory trace that renders items easier to retrieve during subsequent test phases.

Future ERP work in the domain of the cognitive aging of memory should involve the search for individual differences. Changes in ERP parameters such as component amplitude and scalp distribution among groups of elders characterized as either high- or low-performers on the basis of memory performance, neuropsychological test performance, and/or other demographic variables (e.g., education) should enable the investigator to determine if the observed differences are "compensatory" or "inefficient" (see Cabeza, 2001 for a review; Cabeza, 2002 for a synthesis; see Logan, Sanders, Snyder, Morris, & Buckner, 2002 for a very recent example).

Recency/Recognition Memory

This kind of strategy has been employed in an ERP study of memory performed by Fabiani et al. (1999). This study was a follow-up of our previous behavioral recency/recognition investigation (Fabiani & Friedman, 1997), with the addition of ERP recording. In this adaptation of the recency/recognition paradigm, a large number of pictures or words were first presented singly in continuous sequence. These are labeled "information only" trials. This information only phase was followed by intermixed information only and test trials, with the latter comprised of pairs of stimuli. Test trials were identified by a ? appearing in the middle of the pair. Subjects were instructed to memorize the stimuli for subsequent testing within the succeeding sequence of trials. For all test trials, subjects were instructed that they were to press the button corresponding to the side of the object or word that was presented most recently. On *recency only trials*, the pair consisted of two previously presented old items, whereas on *recognition only trials*, there was one old and one new item. An important aspect of this paradigm is that subjects need not be aware of whether the trial is testing recency or recognition memory, as the procedure is identical in the two cases and the trials are intermixed. Thus, any performance difference observed between recency and recognition cannot be attributed to differences in task requirements.

In the earlier investigation by Fabiani and Friedman (1997), an age-related dissociation between recency and recognition performance

was observed with pictorial stimuli: the young and old did not differ in recognition performance, but did differ reliably for recency performance. Moreover, the young, but not the old, showed above-chance recency performance. In an attempt to link their findings with the “frontal lobe deficit” hypothesis of cognitive aging (Albert & Kaplan, 1980), Fabiani and Friedman (1997) correlated word and picture recency and recognition performance with scores on the WCST. Whereas word and picture recency memory performance were correlated with two aspects of WCST performance, word and picture recognition performance were not.

Because of this earlier finding (Fabiani & Friedman, 1997), only pictures of common objects were employed in the Fabiani et al. (1999) investigation. Moreover, due to our interest in individual differences in the aging population, the elderly participants were categorized according to SES, and the ERP data were assessed separately for low- and high-SES

groups. The high-SES group also had experienced a greater number of years of education. If the compensation hypothesis has merit, then we expected that ERP waveform morphology would differ between the high- and low-SES groups and would be associated with higher performance levels in the high-SES group. The data reported below should be considered preliminary, as only a small subset of analyses has been performed as of the writing of this paper. A detailed report of these findings is in preparation.

The Old-High and Old-Low groups did not differ reliably on recognition performance. However the Old-High group (mean = 60%) outperformed the Old-Low group (mean = 50% or chance performance) during recency trials. Moreover, while the young adults (mean = 63%) produced better performance than the Old-Low subjects, the Old-High and young adults did not differ in recency accuracy.

Figure 5 depicts the grand averaged ERPs in the young adult group and in the low- and

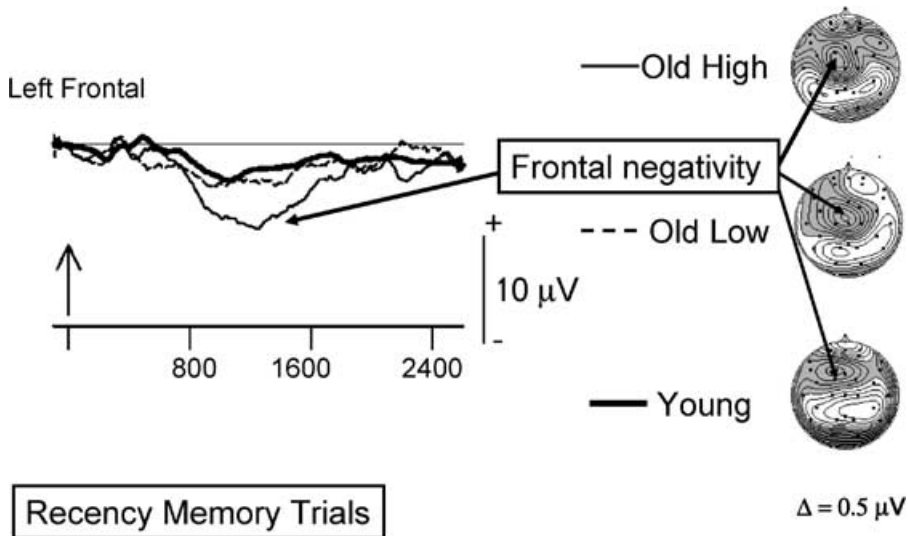


Fig. 5. Grand mean ERPs elicited by correctly identified recency trials in three groups of participants. The Old-High group ($N = 8$) is comprised of subjects with high educational levels; the Old-Low group ($N = 7$) is comprised of subjects with low levels of educational attainment. The young group is comprised of 16 young adults subjects. The data are depicted at a left prefrontal electrode site where the differences among groups was greatest. Note the large negativity in the waveforms of the Old-High group. The surface voltage scalp distributions (SP data computed as the averaged voltage between 985 and 1220 ms) are depicted to the right of the waveforms. The Δ refers to the separation (in μV) between isopotential lines. Small filled squares represent the recording sites. The shaded areas reflect negative activity, the unshaded areas, positive activity.

high-SES groups. As the groups did not differ on recognition trials, only the ERPs for recency trials are depicted at a left prefrontal scalp site where the differences were largest. The ERPs shown in Figure 5 are associated with correctly identified recency test trials. Note that the waveforms in the Old-High group show a considerably larger negativity than either the young or the Old-Low groups.

The negativity does not appear to reflect qualitatively different cognitive activity in the two groups of older adults, as the topographic maps look highly similar, with the maps of the young and both older age groups showing centrally oriented negative foci. This suggests that similar underlying neural networks were recruited. However, for the Old-High subjects, but not the young or the Old-Low group, this negative activity was much larger during recency trials than recognition trials (the latter are not depicted). These recency versus recognition ERP comparisons appear to mirror directly the performance data, that is, no differences between Old-High and Low groups during recognition trials, but a reliable difference between these groups during recency trials. In combination with the finding that the Old-High group did not differ from the young adult group in accuracy of recency judgments, these data suggest the possibility that the larger, frontally oriented negativity reflects compensatory neural activity in the Old-High SES group.

In the Fabiani et al. (1999) study, the late negative activity peaked (at approximately 900 ms) some 300–500 ms earlier than the mean reaction time indicative of the recency decision (these were, respectively for young and old, about 1200 and 1400 ms). Therefore, it is conceivable that the negative activity could have reflected the central, causative brain event leading to the retrieval of recency information. On the other hand, it could also have reflected the brain event indicating the prefrontal cortex's signaling more posterior regions to retrieve the recency information. However, these arguments are speculative pending more detailed analyses and further studies in which the cognitive processes reflected by this ERP component are explored in greater detail via experimental manipulation.

STUDIES OF WORKING MEMORY

The previous episodic memory data suggest that the Old-High group's performance was maintained at a level commensurate with the young by recruiting prefrontal cortical mechanisms to a greater extent than the Old-Low group. The ERP data described throughout this review, albeit indirect with respect to spatial resolution within the brain, suggest that the frontal lobes play a critical role in age-related changes in cognition. Based on relatively more direct measures of hemodynamic areas of activation in the brain, such as PET and fMRI, age-related changes in working memory also appear to be due, at least in part, to changes in frontal lobe function with increasing age (Jonides et al., 2000; Rypma & D'Esposito, 2000). Hence, the next study I will describe sought to determine if ERP and behavioral measures of working memory would also suggest a frontal lobe locus of age-related differences in working memory.

Gaeta et al. (submitted) presented single digits sequentially in strings whose length was either 4, 5, 7, 9, or 11 digits. During the working memory task (WM), subjects were instructed to remember, in order of presentation, the last four digits for a subsequent match/nonmatch probe test. During the short term memory task (STM), participants were asked to remember the first four digits for the subsequent match/nonmatch probe test. For both, a test stimulus was comprised of four digits in the same or different order from the four relevant digits in the previous study string. A match occurred if the probe stimulus was identical in sequence to the four to-be-remembered digits. During the study phases of the STM task, the fourth digit was the last one that needed to be encoded for the subsequent match/nonmatch task. By contrast, during the study phases for the WM task, the fifth digit was the first one to signal that the contents of WM needed to be updated.

STM performance did not differ between the age groups, whereas the older subjects showed longer RTs and a somewhat lower percentage of hits and a greater percentage of false alarms in the WM task. The top row of Figure 6 depicts the ERPs elicited by the fourth and fifth digits during the study phase for the WM task in the young

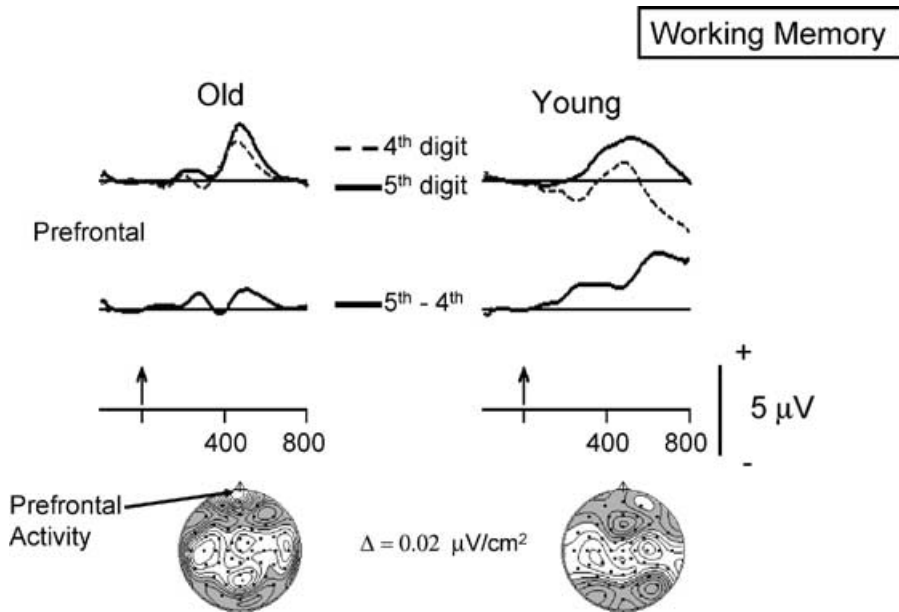


Fig. 6. Grand mean ERPs averaged across subjects within each age group elicited by the fourth (dashed lines) and fifth (solid lines) digits in the working memory task, recorded at a midline prefrontal scalp site. The fifth digit signaled the need to update the contents of working memory. Arrows mark stimulus onset. Depicted below the time lines are the CSD scalp distributions based on the difference waveforms (fifth digit ERP – fourth digit ERP) between a period of 435 and 535 ms poststimulus. Note the area of prefrontal scalp activity present in the data of the elderly but not the young. The ERP data have been collapsed across all study strings. The Δ refers to the separation (in $\mu\text{V}/\text{cm}^2$) between isopotential lines. Small filled squares represent the recording sites. The shaded areas reflect negative activity, the unshaded areas, positive activity. Modified from Gaeta et al. (submitted).

and old age groups. Under STM conditions (not depicted), a positive component of maximum amplitude (peak latency ~ 500 – 600 ms) was always elicited by the fourth stimulus in a study string. This stimulus was the last one that needed to be encoded for the subsequent match/nonmatch task and, therefore, delivered all of the task-relevant information (Sutton, Tueting, Zubin, & John, 1967). There were no age differences in ERP parameters during the STM task. Under WM conditions, the positive component of greatest amplitude was always elicited by the fifth digit in the study string, as shown in the top row of waveforms in Figure 6. As described earlier, this digit was the first to indicate that the contents of WM needed to be updated.

To determine the difference due to the necessity to update WM, difference waveforms were computed by subtracting the ERPs elicited

by the fourth digit from the ERPs elicited by the fifth digit. These are depicted in the second row of waveforms shown in Figure 6. There is a clear difference in amplitude between the young and old age groups; however, this difference did not reach the appropriate level of significance. Nevertheless, as shown in the CSD maps of scalp activity (depicted below each age group's waveforms), the old show an area of prefrontal scalp positive activity, which is not demonstrated by the young. This difference in topography was reliable.

This prefrontal activity in the data of the elderly might reflect the recruitment of “executive processes” required to manage the greater informational demands of the WM task. The frontal focus observed for the elderly, but not the young, may be indicative of compensation for a decline in the efficacy of the updating process, as

the elderly performed at a slightly lower level than the young. This latter interpretation is consistent with hemodynamic imaging studies that have provided evidence of age-related differences in frontal lobe activity during working memory tasks (Grady et al., 1994; Jonides et al., 2000).

SUMMARY OF FINDINGS

In this fairly diverse and highly selected set of experiments, two themes stand out. First, when it has been specifically assessed, a good deal of variability in both the behavioral and ERP responses of elderly samples of participants has been observed. This variability can be explored to infer some of the putative mechanisms responsible for age-related change in cognition. Second, to the extent that ERP recordings from the frontal areas of the scalp are manifestations of the computations of prefrontal cortex (see below for a discussion of this point), the majority of the studies reviewed suggest involvement of the frontal lobes in many of these age-associated changes in cognition. In the oddball experiments, older participants appear to continue to utilize presumed prefrontal cortical processes long after the young have apparently stopped their use (Fabiani & Friedman, 1995). This is true of a subset of the elderly whose putative frontal lobe function is poorer than that of their age-equivalent, higher functioning counterparts (Fabiani, Friedman et al., 1998). The poorer performing frontal lobe subjects show target P3 responses that are characterized by a frontally oriented scalp distribution, in contrast to the higher functioning elderly who demonstrate a parietal-maximal P3 scalp distribution similar to that of young adults. In the study of encoding for subsequent episodic memory testing, older adults do not demonstrate activity over LIPS, suggesting, based on hemodynamic studies (see Cabeza, 2001), that they may not have encoded the items to “deep” (i.e., semantic) levels, which would have ensured higher retrieval success rates at test (Friedman, 2002). Moreover, the older subjects also show bilateral areas of prefrontal scalp activity, whereas the young adults show activity that is

highly focused about the prefrontal midline of the scalp. These results should be followed up by studies that attempt to determine whether individual differences in the extent of LIPS and prefrontal scalp activity predict differences in episodic memory performance. The investigation of recency/recognition memory (Fabiani et al., 1999) suggests that those subjects who have high levels of SES and education produce the largest amplitude activity over frontal scalp in association with successfully identified recency trials. By contrast with the study of individual differences in target P3 responses (Fabiani, Friedman et al., 1998), this result suggests that frontal cortex is activated to a greater extent by participants who show higher levels of frontal and intellectual functioning (see below for more discussion). Finally, in investigations of working memory (Gaeta et al., submitted), prefrontal scalp activity is greater for the old compared to the young, again suggesting that, as for the oddball data, older adults may “compensate” for the deleterious effects of aging by continually activating frontal regions when the young no longer need to do so.

METHODOLOGICAL CONSIDERATIONS

Does Frontally Oriented ERP Activity Imply Frontal Cortical Activity?

One difficulty in unequivocally interpreting the results of these studies is that it is difficult to infer the intracranial generators of ERP activity based solely on inspection of the distribution of amplitudes on the scalp surface (see Picton, Lins, & Scherg, 1995 for detailed discussion). Complex modeling algorithms (e.g., Scherg, 1990) are typically required. In addition, converging sources of information are necessary, such as ERP studies of patients with circumscribed lesions, experimental neuropsychological studies of such patients, intracranial ERP and fMRI investigations. Some modeling studies do suggest that the anterior aspect of the target P3 receives contributions from regions in frontal cortex (Friedman, Fabiani, & Simpson, 1996), and patient lesion studies are generally consistent with this view (e.g., Knight, Staines, Swick, & Chao, 1999). Moreover, the results of intracranial ERP (Halgren et al., 1998) and fMRI

studies of variants of the oddball task (Friedman et al., 2001) also resonate with this conclusion. Similarly, activity recorded over left inferior prefrontal scalp during the encoding study by Friedman and Trott (2000) appears to have counterparts in the neuroimaging literature (Wagner, in press), as does the electrical activity over medial prefrontal scalp observed during the working memory task described here (e.g., Jonides et al., 2000). Hence, based solely on scalp-recorded ERP data, one cannot come to a definitive conclusion; however, taken together, the evidence from these disparate research domains does implicate frontal cortex as playing a critical role in age-related changes in cognition.

Reconciling Increased Activity Over Frontal Scalp in High- and Low-SES and High- and Low-WCST Performers

In the study by Fabiani, Friedman et al. (1998), poor WCST performers showed greater target P3 activity over prefrontal scalp, whereas good WCST performers showed the opposite pattern, greater target P3 activity over parietal scalp. By contrast, in the investigation of recency/recognition memory by Fabiani et al. (1999), high-SES participants showed greater activity over prefrontal scalp than did the low-SES subjects. These participants also performed better on the WCST than did their lower-SES counterparts. How can these two sets of findings be reconciled? First, it is useful to note that these findings occurred for two different ERP components, one a positivity (the target P3) and the other a negativity, each elicited in two extremely different tasks, the former during deviance detection, the latter during recency retrieval. Because it is quite likely that different regions of frontal cortex have different functional roles (Cabeza & Nyberg, 2000), this difference may not be surprising. For example, the target P3 response shows a prefrontal scalp distribution that is oriented about the scalp midline, whereas the negativity shows a more posterior frontal topography. This suggests that each is emanating from different regions of the frontal cortex or, if these regions are not the generators of these activities per se, that the two tasks are accomplished by at least partially nonoverlapping neural networks. Thus, the reasons for increased activity on the part

of good and poor performers in the two tasks are not likely to be similar.

One Scientist's Compensation is Another's Inefficiency

Finally, how one determines what is compensatory and what is inefficient appears to be a relatively difficult problem. It is not necessary to go through those arguments here, as they have been outlined in detail by others (e.g., Cabeza, 2001; Grady, 2000; see also Park, 2002). Generally, it is not at all clear, at this stage of knowledge, what kind of pattern should be considered "compensatory," and what kind should be considered "inefficient." This is due, in part, to the small number of cognitive aging studies that have considered these factors, and also to the small number of investigations that have been specifically designed with these questions in mind.

A very recent study Logan et al. (2002), however, does shed some light on these issues. In experiment one, verbal and nonverbal (face) materials were encoded for a subsequent recognition test with self-initiated encoding strategies. The results indicated that young adults recruited anterior/ventral prefrontal regions in a material-specific manner. Older adults showed under-recruitment of these areas, regions typically associated with the retrieval of semantic information. However, when deep (semantic) encoding instructions were given in Experiment 2, young/old as well as old/old adults showed enhanced activation in these areas relative to the intentional encoding conditions, suggesting that the initial under-activation arose from a failure to spontaneously recruit these regions in the service of deep levels of semantic analysis. These regions were highly similar to those activated by the young. Nevertheless, despite this augmented activation, old/old (compared to young/old) adults showed nonselective recruitment of left and right prefrontal regions – that is, paradoxical laterality – regions in right prefrontal cortex were activated by verbal materials and regions in left prefrontal cortex were activated by nonverbal materials. The authors concluded that there were two forms of age-associated change that they termed "under recruitment," and "nonselective recruitment." They further suggested that the

former might be amenable to change via cognitive training, because when directed to encode deeply both groups of older adults could do so. Because the old/old and not the young/old adults showed “nonselective recruitment,” the authors also suggested that this type of recruitment might not be amenable to cognitive remediation, and might be associated with (unalterable) decline in cognition as people age.

Another very recent investigation by Cabeza et al. (2002) also speaks to these issues and comes to somewhat similar conclusions. Cabeza and colleagues screened their elderly adults prior to PET data collection and, on this basis, divided their elderly sample into low- and high-performers on a set of long-term memory tasks. Subjects studied lists of words and then were tested, while in the scanner, on tests of recall and source memory. During the test phase, the young and old-high groups did not differ reliably in performance accuracy, whereas both showed significantly higher performance than the old-low group. Cabeza et al.’s young participants activated left prefrontal cortex (ventro- and dorsolateral) during the recall of studied items, but right prefrontal cortex (dorsolateral and anterior) during the retrieval of source information. With the exception of a lack of left dorsolateral activity during recall, the old-low performing group showed a similar pattern of activations during source retrieval and recall. The high-performing elderly group showed a different pattern of activation compared to both the young and old-low groups – right anterior prefrontal activation (shown by both young and old-low groups), in addition to left anterior activations (not shown by young and old-low groups) during source retrieval. These results were interpreted by Cabeza et al. (2002) to mean that the old-high group “compensated” for age-related changes via the reorganization of neural networks in the service of the more difficult source retrieval task, showing a reduction in the hemispheric asymmetry of prefrontal activations. Because the old-low group performed worse than the old-high group and did not reorganize neural recruitment, their data were interpreted as consistent with an “inefficient” use of the neurocognitive networks that were recruited.

These two studies make the point that the issue of “compensation” and “inefficiency” is fairly complex, and will require further investigation before firm conclusions can be reached. For example, it should be noted that the Logan et al. (2002) data are not without contradiction.³ Using the same abstract/concrete encoding task as Logan et al., Stebbins et al. (2002) found that left prefrontal cortical activity during encoding was weaker in the old (whereas Logan et al. found no difference between young and old). Nevertheless, the Cabeza et al. and Logan et al. designs and results suggest that, by including several levels of experimental manipulation as well as more groups of older adults stratified by age, and/or performance levels, hypotheses concerning “compensation” or “inefficiency” could be more easily formulated, and results might not be as subject to post hoc interpretation as appears to be the case currently.

As suggested by the Cabeza et al. (2002) data, one potential solution may be to, a priori, screen the elderly sample on the basis of critical performance and demographic measures, such as long-term memory function, frontal lobe function, and/or educational levels and socio-economic status. The choice would depend upon the hypotheses under study. For example, if the “frontal lobe deficit” hypothesis was under investigation, one might choose frontal lobe assessments for characterizing the sample. The elderly sample would then be categorized on the basis of high- and low-performance on one or more of these indices. As mentioned above, an advantage of this strategy is that predictions with respect to “compensatory” versus “inefficient” neurocognitive patterns can be made a priori rather than post hoc. Under these circumstances, a scenario might be that good performers recruit a compensatory neural network and do not differ behaviorally from the young on the experimental task in question; by contrast, poor performers might recruit a similar network to the young, but use it “inefficiently,” resulting in poorer performance than the young and the high performing old. As detailed earlier, this analysis strategy has

³I thank Dr. Roberto Cabeza for pointing this out to me.

been used successfully with fMRI data by Cabeza et al. (2002), and with ERP data by Fabiani et al. (1999).

CONCLUSIONS

This review is based on only a few highly selected sets of ERP data from this laboratory. Nevertheless, it is clear that we are at a very early stage of understanding the basis of age-related compensatory neural changes based on ERP data. To my knowledge, aside from the ERP studies described in the current paper, there are no other published ERP investigations that have examined specifically the issue of compensation. Hence, it is important to be cautious in attempting to draw conclusions at this point. The ERP provides fine-grained temporal precision, which is unavailable with current fMRI methods. Note that, in all of the ERP investigations described in the current paper, the critical neural events reflecting either age-related differences or condition-related differences occurred within the first 250–800 ms poststimulus. On the other hand, fMRI techniques allow excellent spatial resolution, which is more difficult to infer with the ERP method. Hence, an approach in which both techniques are combined will most likely lead to breakthroughs in knowledge. This kind of approach has been successful in other domains (see Rugg, 1998 and Luck, 1999 for discussions) but, to date, has not been applied to the study of cognitive aging. The future looks bright, and further research will undoubtedly yield a better understanding of the mechanisms underlying preservation and dissolution in cognition as humans age.

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REFERENCES

- Albert, M.S., & Kaplan, E. (1980). Organic implications of neuropsychological deficits in the elderly. In L.W. Poon, L.S. Fozard, D. Cermak, L.D. Arenberg, & L.W. Thompson (Eds.), *New directions in memory and aging: Proceedings of the George A. Talland Memorial Conference* (pp. 403–432). Hillsdale: Laurence Erlbaum.
- Anderson, N.D., & Grady, C.L. (2001). Functional imaging in cognitively intact aged people. In P.R. Hof & C.V. Mobbs (Eds.), *Functional neurobiology of aging* (pp. 211–225). New York: Academic Press.
- Cabeza, R. (2001). Cognitive neuroscience of aging: Contributions of functional neuroimaging. *Scandinavian Journal of Psychology*, *42*, 277–286.
- Cabeza, R. (2002). Hemispheric asymmetry reduction in older adults: The HAROLD model. *Psychology and Aging*, *17*, 85–100.
- Cabeza, R., Anderson, N.D., Locantore, J.K., & McIntosh, A.R. (2002). Aging gracefully: Compensatory brain activity in high-performing older adults. *Neuroimage*, *17*, 1394–1402.
- Cabeza, R., Mangels, J., Nyberg, L., Habib, R., Houle, S., McIntosh, A.R., & Tulving, E. (1997). Brain regions differentially involved in remembering what and when: A PET study. *Neuron*, *19*, 863–870.
- Cabeza, R., & Nyberg, L. (2000). Imaging cognition II: An empirical review of 275 PET and fMRI studies. *Journal of Cognitive Neuroscience*, *12*, 1–47.
- Coffey, C.E., Saxton, J.A., Ratcliff, G., Bryan, R.N., & Lucke, J.F. (1999). Relation of education to brain size in normal aging: Implications for the reserve hypothesis. *Neurology*, *53*, 189–196.
- Craik, F.I.M., & McDowd, J.M. (1987). Age differences in recall and recognition. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *13*, 474–479.
- Demb, J.B., Desmond, J.E., Wagner, A.D., Vaidya, C.J., Glover, G.H., & Gabrieli, J.D.E. (1995). Semantic encoding and retrieval in the left inferior prefrontal cortex: A functional MRI study of task difficulty and task specificity. *Journal of Neuroscience*, *15*, 5870–5878.
- Fabiani, M., & Friedman, D. (1995). Changes in brain activity patterns in aging: The novelty oddball. *Psychophysiology*, *32*, 579–594.
- Fabiani, M., & Friedman, D. (1997). Dissociations between memory for temporal order and recognition memory in aging. *Neuropsychologia*, *35*, 129–141.

- Fabiani, M., Friedman, D., & Cheng, J.C. (1998). Individual differences in P3 scalp distribution in older adults, and their relationship to frontal lobe function. *Psychophysiology*, *35*, 698–708.
- Fabiani, M., Friedman, D., Cheng, J., Wee, E., & Trott, C.T. (1999). Use it or lose it: Effects of aging and education on brain activity in the performance of recency and recognition memory tasks. *Journal of Cognitive Neuroscience*, *11*(Suppl.), 73.
- Fabiani, M., Gratton, G., Corballis, P.M., Cheng, J., & Friedman, D. (1998). Bootstrap assessment of the reliability of maxima in surface maps of brain activity of individual subjects derived with electrophysiological and optical methods. *Behavior Research Methods and Instrumentation*, *30*, 78–86.
- Friedman, D. (2000). Event-related brain potential investigations of memory and aging. *Biological Psychology*, *54*, 175–206.
- Friedman, D. (2002). *Age-associated changes in episodic memory: An ERP perspective*. Paper presented at a Conference entitled, Binding in Human Memory: A Neurocognitive Approach, Saarbrücken, Germany, May.
- Friedman, D., Cycowicz, Y.M., & Gaeta, H. (2001). The novelty P3: An event-related brain potential (ERP) sign of the brain's evaluation of novelty. *Neuroscience and Biobehavioral Reviews*, *25*, 355–373.
- Friedman, D., Fabiani, M., & Simpson, G.V. (1996). Brain electrical activity in aging: Different age-related intracranial configurations revealed by source localization. *Neuroimage*, *3*, S576.
- Friedman, D., & Johnson, R. (2000). Event-related potential (ERP) studies of memory encoding and retrieval: A selective review. *Microscopy Research and Technique*, *51*, 6–28.
- Friedman, D., & Trott, C. (2000). An event-related potential study of encoding in young and older adults. *Neuropsychologia*, *38*, 542–557.
- Gaeta, H., Friedman, D., & Hurlie, J. (submitted). Age-related differences in the neural correlates of working memory.
- Glisky, E.L., Polster, M.R., & Routhieux, B.C. (1995). Double dissociation between item and source memory. *Neuropsychology*, *9*, 229–235.
- Glisky, E.L., Rubin, S.R., & Davidson, P.S.R. (2001). Source memory in older adults: An encoding or retrieval problem? *Journal of Experimental Psychology – Learning, Memory, and Cognition*, *27*, 1131–1146.
- Grady, C.L. (2000). Functional brain imaging and age-related changes in cognition. *Biological Psychology*, *54*, 259–281.
- Grady, C.L., & Craik, F.I. (2000). Changes in memory processing with age. *Current Opinion in Neurobiology*, *10*, 224–231.
- Grady, C.L., Maisog, J.M., Horwitz, B., Ungerleider, L.G., Mentis, M.J., Salerno, J.A., Pietrini, P., Wagner, E., & Haxby, J.V. (1994). Age-related changes in cortical blood flow activation during visual processing of faces and location. *Journal of Neuroscience*, *14*, 1450–1462.
- Greenwood, P.M. (2000). The frontal aging hypothesis evaluated. *Journal of the International Neuropsychological Society*, *6*, 705–726.
- Halgren, E., Marinkovic, K., & Chauvel, P. (1998). Generators of the late cognitive potentials in auditory and visual oddball tasks. *Electroencephalography and Clinical Neurophysiology*, *106*, 156–164.
- Hashtroudi, S., Parker, E.S., Luis, J.D., & Reisen, C.A. (1989). Generation and elaboration in older adults. *Experimental Aging Research*, *15*, 73–78.
- Henson, R.N.A., Rugg, M.D., Shallice, T., Josephs, O., & Dolan, R.J. (1999). Recollection and familiarity in recognition memory: An event-related functional magnetic resonance imaging study. *Journal of Neuroscience*, *19*, 3962–3972.
- Howard, D.V., Heisey, J.G., & Shaw, R.J. (1986). Aging and the priming of newly learned associations. *Developmental Psychology*, *22*, 78–85.
- Jonides, J., Marshuetz, C., Smith, E.E., Reuter-Lorenz, P.A., Koeppe, R.A., & Hartley, A. (2000). Age differences in behavior and PET activation reveal differences in interference resolution in verbal working memory. *Journal of Cognitive Neuroscience*, *12*, 188–196.
- Knight, R.T. (1990). Neural mechanisms of event-related potentials: Evidence from human lesion studies. In J.W. Rohrbaugh, R. Johnson, & R. Parasuraman (Eds.), *Event-related brain potentials* (pp. 3–18). New York City: Academic Press.
- Knight, R.T., Staines, W.R., Swick, D., & Chao, L.L. (1999). Prefrontal cortex regulates inhibition and excitation in distributed neural networks [In Process Citation]. *Acta Psychologica*, *101*, 159–178.
- Li, K.Z., Lindenberger, U., Freund, A.M., & Baltes, P.B. (2001). Walking while memorizing: Age-related differences in compensatory behavior. *Psychological Science*, *12*, 230–237.
- Logan, J.M., Sanders, A.L., Snyder, A.Z., Morris, J.C., & Buckner, R.L. (2002). Under-recruitment and non-selective recruitment: Dissociable neural mechanisms associated with aging. *Neuron*, *33*, 827–840.
- Luck, S.J. (1999). Direct and indirect integration of event-related potentials, functional magnetic resonance images, and single-unit recordings. *Human Brain Mapping*, *8*, 115–120.
- Mark, R.E., & Rugg, M.D. (1998). Age effects on brain activity associated with episodic memory retrieval: An electrophysiological study. *Brain*, *121*, 861–873.

- Mayeux, R., Small, S.A., Tang, M., Tycko, B., & Stern, Y. (2001). Memory performance in healthy elderly without Alzheimer's disease: Effects of time and apolipoprotein-E. *Neurobiology of Aging*, *22*, 683–689.
- Mayeux, R., Stern, Y., Rosen, J., & Leventhal, J. (1981). Depression, intellectual impairment, and Parkinson disease. *Neurology*, *31*, 645–650.
- McEvoy, L.K., Pellouchoud, E., Smith, M.E., & Gevins, A. (2001). Neurophysiological signals of working memory in normal aging. *Cognitive Brain Research*, *11*, 363–376.
- McEvoy, L.K., Smith, M.E., & Gevins, A. (1998). Dynamic cortical networks of verbal and spatial working memory: Effects of memory load and task practice. *Cerebral Cortex*, *8*, 563–574.
- Mountain, M.A., & Snow, W.G. (1993). Wisconsin Card Sorting Test as a measure of frontal pathology: A review. *The Clinical Neuropsychologist*, *7*, 108–118.
- Nielsen-Bohman, L., & Knight, R.T. (1999). Prefrontal cortical involvement in visual working memory. *Cognitive Brain Research*, *8*, 299–310.
- Opitz, B., Mecklinger, A., Von Cramon, D.Y., & Kruggel, F. (1999). Combining electrophysiological and hemodynamic measures of the auditory oddball. *Psychophysiology*, *36*, 142–147.
- Paller, K.A., & Wagner, A.D. (2002). Transforming experience into memory: Observations of mind and brain. *Trends in Cognitive Sciences*.
- Park, D.C. (2002). Judging meaning improves function in the aging brain. *Trends in Cognitive Science*, *6*, 227–229.
- Pauli, P., Lutzenberger, W., Rau, H., Birbaumer, N., Rickard, T.C., Yaroush, R.A., & L.E. Byrne, J. (1994). Brain potentials during mental arithmetic: Effects of extensive practice and problem difficulty. *Cognitive Brain Research*, *2*, 21–29.
- Picton, T.W., Lins, O.G., & Scherg, M. (1995). The recording and analysis of event-related potentials. In R. Johnson, Jr. & J.C. Baron (Eds.), *Handbook of neuropsychology* (Vol. 10, pp. 3–73). Amsterdam: Elsevier.
- Raichle, M.E., Fiez, J.A., Videen, T.O., MacLeod, A.K., Pardo, J.V., Fox, P.T., & Petersen, S.E. (1994). Practice-related changes in human brain functional anatomy during nonmotor learning. *Cerebral Cortex*, *4*, 8–26.
- Rowe, J.B., Toni, I., Josephs, O., Frackowiak, R.S., & Passingham, R.E. (2000). The prefrontal cortex: Response selection or maintenance within working memory? *Science*, *288*, 1656–1660.
- Rugg, M.D. (1998). Convergent approaches to electrophysiological and hemodynamic investigations of memory. *Human Brain Mapping*, *6*, 394–398.
- Rypma, B., & D'Esposito, M. (2000). Isolating the neural mechanisms of age-related changes in human working memory. *Nature Neuroscience*, *3*, 509–515.
- Salthouse, T.A., Fristoe, N., & Rhee, S.H. (1996). How localized are age-related effects on neuropsychological measures? *Neuropsychology*, *10*, 272–285.
- Scherg, M. (1990). Fundamentals of dipole source analysis. In F. Grandori, M. Hoke, & G.L. Romani (Eds.), *Auditory evoked magnetic fields and potentials* (Vol. 6, pp. 40–69). Basel: Karger.
- Schmand, B., Smit, J., Lindeboom, J., Smits, C., Hooijer, C., Jonker, C., & Deelman, B. (1997). Low education is a genuine risk factor for accelerated memory decline and dementia. *Journal of Clinical Epidemiology*, *50*, 1025–1033.
- Snodgrass, J.G., & Corwin, J. (1988). Pragmatics of measuring recognition memory: Applications to dementia and amnesia. *Journal of Experimental Psychology General*, *117*, 34–50.
- Spencer, W.D., & Raz, N. (1995). Differential effects of aging on memory for content and context: A meta-analysis. *Psychology and Aging*, *10*, 527–539.
- Stebbins, G.T., Carrillo, M.C., Dorfman, J., Dirksen, C., Desmond, J.E., Turner, D.A., Bennett, D.A., Wilson, R.S., Glover, G., & Gabrieli, J.D. (2002). Aging effects on memory encoding in the frontal lobes. *Psychology and Aging*, *17*, 44–55.
- Stern, Y. (2002). What is cognitive reserve? Theory and research application of the reserve concept. *Journal of the International Neuropsychological Society*, *8*, 448–460.
- Stern, Y., Albert, S., Tang, M.X., & Tsai, W.Y. (1999). Rate of memory decline in AD is related to education and occupation: Cognitive reserve? *Neurology*, *53*, 1942–1947.
- Sutton, S., Braren, M., Zubin, J., & John, E.R. (1965). Evoked potential correlates of stimulus uncertainty. *Science*, *150*, 1187–1188.
- Sutton, S., Tueting, P., Zubin, J., & John, E.R. (1967). Information delivery and the sensory evoked potential. *Science*, *155*, 1436–1439.
- Trott, C.T., Friedman, D., Ritter, W., Fabiani, M., & Snodgrass, J.G. (1999). Episodic priming and memory for temporal source: Event-related potentials reveal age-related differences in prefrontal functioning. *Psychology and Aging*, *14*, 390–413.
- Wagner, A.D. (2002). Cognitive control and episodic memory: Contributions from prefrontal cortex. In L.R. Squire & D.L. Schacter (Eds.), *Neuropsychology of memory* (3rd ed.), pp. 174–192. Cambridge: MIT Press.
- Wagner, A.D., Schacter, D.L., Koutstaal, M.R.W., Maril, A., Dale, A.M., Rosen, B.R., & Buckner, R.L. (1998). Building memories: Remembering and forgetting of verbal experiences as predicted by brain activity. *Science*, *281*, 1188–1191.

- Wegesin, D.J., Friedman, D., Varughese, N., & Stern, Y. (2002). Age-related changes in source memory retrieval: An ERP replication and extension. *Cognitive Brain Research, 13*, 323–338.
- West, R. (2001). The transient nature of executive control processes in younger and older adults. *European Journal of Cognitive Psychology, 13*, 91–105.
- Wilding, E.L. (2001). Event-related functional imaging and episodic memory. *Neuroscience and Biobehavioral Reviews, 25*, 545–554.
- Wilding, E.L., & Rugg, M.D. (1996). An event-related potential study of recognition memory with and without retrieval of source. *Brain, 119*, 889–905.