AGING AND SPEED OF BEHAVIOR: Possible Consequences for Psychological Functioning

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INTRODUCTION

Over one hundred years have passed since Francis Galton studied older persons’ speed of reaction to sudden sounds and light. Much of the early research on the speed of response sketched the outlines of issues, some of which are still investigated today. In this review we present a brief overview of some of the important historical contributions to our understanding of speed of response and age-related changes. We limit our review to changes in speed in
normal aging, that is, in relatively disease-free older adults. Because we are interested in how to think about speed of response and how it relates to other cognitive processes, we also limit our review to the biological basis of speed of response, to cognitive correlates of changes in speed, and to some of the consequences of slowed reaction time for intellectual functioning. In the process, we also review some integrative lines of thinking about aging that biologists, psychologists, and sociologists have suggested. In this review, aging is defined as "the regular changes that occur in mature, genetically representative, organisms living under representative environmental conditions" (Birren & Renner 1977, p. 4).

BACKGROUND

In 1884, Galton organized 17 different "anthropometric measurements," including reaction time, for use at the International Health Exhibition in London (Galton 1885). Nearly 9400 subjects aged 5–80 participated, marking the first lifespan reaction-time experiment with enough data points for LISREL modeling analyses. Subsequent analyses of Galton's data by Koga & Morandt (1923) revealed that auditory and visual reaction times were more correlated with each other than auditory reaction time was correlated with auditory acuity or visual reaction time was correlated with visual acuity. Koga & Morandt's analyses provided the first hint that the slowness in behavior shown by older persons lay principally within the central nervous system rather than in the peripheral sensory systems.

In the same manner, Birren & Botwinick (1955) showed that peripheral nerve conduction velocity was not associated with age-related slowing in speed of response. They found that finger, foot, and jaw simple reaction time for young and older adults differed by a constant amount. If peripheral factors had played a role, foot reaction time would have been proportionately slower than finger or jaw reaction time. A neurologist, Magladery (1959), came to much the same conclusion after reviewing the neuropsychological literature: "degenerative changes at the periphery in end organs and nerve pathways, if valid, cannot possibly account for more than a small fraction of the prolongation in motor response times encountered in the old" (p. 183).

In a review of the psychological literature nearly 30 years later, Salthouse (1985) confirmed the small contribution of sensory and motor factors to slowing:

The great majority of evidence suggests that sensory and motor factors have only slight effects on speed when stimuli are intense, or responses are simple, as those typically found in aging studies of speeded behavior....The controversy now is not whether peripheral or central mechanisms are responsible for the slowing with age, but rather which particularly central mechanism is the
most fundamental....The available evidence is consistent with the hypothesis that the same mechanisms responsible for the slowing phenomenon also contribute to the other cognitive differences observed with increased age (p. 422).

Both early and more recent attempts to account for the slowing with age have regarded response time as a function of a neural network, which points to a global phenomenon of slowness. In one early formulation, Landahl (1959) noted that both young and older adult simple reaction times were faster to high-intensity stimuli. In a model of age differences in reaction time, Landahl introduced terms for stimulus intensities and the number of fibers in a response pathway. At high intensities of signals, age-related differences in response time were proportional to the number of fibers in the pathway. Landahl also examined the age-related tendency for disproportionate increase in reaction time under conditions of increasing difficulty (e.g. degraded stimuli).

Some 30 years later, Cerella (1990) expressed his model of age-related slowing in terms of 1. the number of links that are traversed to reach a response and 2. the time delay within each link. Thus, response time latency equals unit time multiplied by the number of links. Cerella's approach was similar to Landahl's but was couched in terms of the prevailing computer metaphor of cognition.

HIERARCHICAL LEVELS OF EXPLANATION

Another historical trend in scientific exploration of aging issues has been the consideration of the level of explanation afforded by a theory or empirical results. In a review of the aging literature, Miles (1942) held a hierarchical notion of how behavior was organized, stating: "Most significant perhaps in the study of psychological ageing is the discovery of a consistent tendency in reference to the hierarchy of mental functions" (p. 75). The notion of different levels of explanation and a hierarchy of functions continues to plague the psychology of aging in theory building and operationalizations of concepts.

It is acceptable to state that an older adult is generally slowed in behavior relative to younger adults. However, the mechanisms whereby the slowing of behavior has an effect on social interactions, decision making, or learning in older adults is an important, but somewhat neglected, question. Intuitively, one suspects that elemental processes, such as inhibition and facilitation, which are closely dependent on neurochemical and neuroanatomical substrata, will in turn influence more complex behaviors such as attention, learning, and reasoning. Without a model of the hierarchical organization of behavior, it is impossible to project the significance of changes at the elemental level to more
complex processes, or to project effects from complex processes downward to the more elemental. Empirical results from other traditions have not added to knowledge and systematic explanations of the principal transformations in behavior during adult life. When constructing theories of age-related changes in behavior, we need to be aware of the level of observations made, the level of theoretical statements about behavior, and the need for greater linkages between discrete components and complex behaviors.

The need to create theoretical links across levels of explanation is not unique to studies of aging. Cacioppo & Berntson (1992) called for a “social neuroscience” in order to place data from different levels of analysis into the same theory for explaining behavior. The Gerontological Society of America has recognized the importance of integrating findings across levels of explanation, such that the theme of the 1994 annual meeting was “Aging cells to aging populations” (Gerontology News, March 1994). Examination of changes across time and between levels of explanation has placed an increasing emphasis on complexity and the dynamic aspects of older adult behavior, in contrast to single variable correlates of chronological age.

Hoyer & Rybash (1994) suggested an example of theory building integrating across levels. They hypothesized that age-related changes in behavior are “based on the emergence and increased differentiation of domain-ordered knowledge specialization” (p. 10). Knowledge, as presentations of events, is continually updated and differentiated on the basis of ever-increasing experience. The representations include sensory information as well as concepts of meaning. Changing representations result in increasing cognitive complexity with age (Hoyer & Rybash 1994).

Although psychologists observe increasing complexity in the older organisms, physiologists note decreasing biological complexity (Angelucci et al 1991, Lipsitz & Goldberger 1992). These divergent conclusions across disciplines may be the result of different definitions of aging. Investigations should define the level of explanation and the independent variables used in addition to the chronological age of subjects. One of the more general and important integrative questions to be asked of human aging is whether age-related changes are governed by energy (metabolic) change or information change (losses or gains in information) (Salthouse 1993a). Insights into hierarchical organization may be gained by examining clusters of behaviors that show increments, maintenance, or decrements with age, and relating them to imputed causes. The issues discussed above have shaped how the following literature review is organized, moving from the physiological correlates of slowing in speed of behavior, through some basic cognitive changes with age, and, finally, to how slowing affects intellectual abilities across age.
REVIEW OF THE LITERATURE

Physiology of Speed

Clues to the neural basis of changes in speed of processing come from studies of subcortical dementia or white matter dementia (Albert et al 1974; Cummings & Benson 1983; Filley et al 1989a,b; Grafman et al 1990; Junque et al 1990; Rao et al 1989). Cortical dementias, such as Alzheimer's disease, attack neurons in the gray matter of the cortex; subcortical dementias, such asBinswanger's disease and multiple sclerosis, cause demyelination of white matter (Filley et al 1989b). In a study of progressive supranuclear palsy, Albert et al (1974) identified four behavioral features of subcortical damage: impaired memory, inability to manipulate previously acquired knowledge, emotional lability, and slowing of information processing. In addition, investigators have linked white matter dementia impairments with frontal impairments (Filley et al 1989a). Frontal lobe dysfunction has been related to the attention and memory deficits seen in older adults as well (Craik et al 1990, Cummings & Benson 1983). Slowing of information processing has been observed in the major subcortical dementias (e.g. AIDS dementia and progressive supranuclear palsy) (Filley et al 1989a). Thus, damage to white matter structures appears to be a good candidate as a contributor to the slowing with age.

Recent magnetic resonance imaging (MRI) studies have indicated that increased damage to white matter [seen as leuko-ariaosis (LA) on an MRI] is linked with cerebrovascular risk and with decreases in speed of information processing in normal older adults (Junque et al 1990, Rao et al 1989). In an MRI study, Rao et al (1989) assessed young and older subjects on a neuropsychological battery that examined a range from motor functioning to intellectual ability. Ten subjects (out of fifty) showed large amounts of LA and had slower simple reaction times than did subjects with little LA. However, the difference in reaction times was not statistically reliable. Junque et al (1990) also used MRI in an examination of older adults who had cerebrovascular risk factors. They found that LA was not correlated with simple reaction time or finger tapping speed, but it was correlated with slowing of complex cognitive processes, as measured by Stroop interference performance. Taken together, these two studies suggest that MRI evaluation of LA may be helpful in identifying the underlying neurological structures involved in the slowing of response time with normal aging and also in specific disease states, such as risk of cerebrovascular accidents, but more refined and standardized measures of response time are needed across studies.

Electrophysiological measures are also used to demonstrate slowing with age (Ball et al 1989, Bashore et al 1989, Brown et al 1983, Marsh et al 1990, Strayer et al 1987, Surwillo & Iyer 1989). Specific components of EEG waves, event-related potentials (ERPs), have been thought to provide a tem-
poral measurement of various stages of information processing. One of the most frequently examined ERP components in aging is the P300, an ERP component thought to indicate context updating or simple memorial processes (Donchin & Coles 1988). Earlier concerns about the reliability of ERP components in older adults have been allayed somewhat by more recent data indicating good reliability for the P300 in older adults (Pollock & Schneider 1992). However, experiments continue to note differences in ERP waveforms between young and older subjects. The significance of this result is unclear.

Bashore (1990) concluded from his detailed survey of the studies of aging and ERPs that slowing in neuronal processing results in behavioral slowing. Furthermore, Bashore suggested that the temporal nature of ERPs can be used to identify more precisely the focus of the decline of processing speed. Significantly, Bashore stated that the latency of the P300 was “a purer measure of age-related changes in higher order CNS processes” compared to reaction time measures (1990, p. 262). Each ERP component latency points to slowing in specific types of cognitive processing. For example, the N100 and N200 are more indicative of age-related slowing in processes related to the immediate use of information and increased P300 latencies are more indicative of slowing in memorial processes (Bashore 1989, 1990).

Tachibana et al (1992) examined age-related slowing of the latencies of the P300a and P300b subcomponents of the P300 in subjects aged 20–90. P300a presumably represented passive processing of novel stimuli, whereas P300b represented active processing of relevant stimuli. Both components increased in latency with increasing age ($r = .62$ with P300a; $r = .64$ with P300b). Although the subcomponents increased in latency with age, the P300b component showed larger amounts of slowing. Tachibana et al (1992) concluded that both active and passive attentional processing are impaired with age, a conclusion that supports generalized slowing with age.

In Looren de Jong et al.’s (1989) study, young and older subjects responded to both rare and frequent letters with the left and right hand. Reaction time did not differ across age groups, but older adults were slowed in P300 latencies, and there was no correlation between slowed P300 latencies and reaction time in older adults. These authors concluded that the dissociation of P300 latency and reaction time may have resulted from fewer resources being devoted to the updating of memorial processes with age while the older adults were responding behaviorally.

Iragui et al (1993) investigated slowing of ERP component latencies in young and older adults in an auditory oddball paradigm. They found that latencies of early ERP components (N100 and P200) were increased with age and P300 latencies showed even larger increases with age. However, the P300 latencies were not highly correlated with behavioral reaction time. Iragui et al (1993) concluded that central cognitive processes (e.g. those assessed by
P300) show larger age effects than do peripheral perceptual processes (e.g. those assessed by N100 and P200) and that simple reaction time tasks are not as sensitive to these subtle age changes as are analyses of ERP components. It appears that an analysis of ERPs can provide information about slowing in specific processes that cannot be gained by single examination of reaction time.

At least one study has examined P300 latency and intellectual ability performance in older adults. O'Donnell et al (1992) elicited P300 components both actively and passively using the oddball paradigm with older adults. Passive P300 components were elicited by having subjects listen to a sequence of rare and frequent tones; active P300 components were elicited by requiring subjects to count the target tones within a prescribed sequence. Subjects were also given a battery of intellectual ability measures. Active and passive P300 latency increased with age, as expected. Each P300 component correlated separately and significantly with specific intellectual abilities after age was partialled out. Passively elicited P300 latencies correlated with verbal learning and memory factors. Active P300 latencies correlated with the general intelligence and concentration factors. The authors concluded that measures of neural integrity, in this case, the P300 ERP component, account for some of the individual differences in intellectual ability, beyond the variance associated with age changes (O'Donnell et al 1992).

Measurement of ERP component waveforms provides a window into the temporal nature of neural processing and, thus, provides clues to the slowing in reaction time with age. Differential slowing of separable components apparently can be linked to cognitive processes with which older adults have difficulties. Specifically, slowing directly impacts memorial processes. Slowing also adversely impacts intellectual functioning. Linking slowed ERP components with behavioral measure of reaction time and complex cognitive processing firmly anchors age-related behavioral slowing in biological factors, possibly more affected by disease states in older adults.

Studies of the effects of exercise and cardiovascular fitness on cognitive functioning in older adults provide an additional line of evidence in support of the biological basis for response slowing (Baylor & Spirduso 1988, Clarkson-Smith & Hartley 1989, 1990, Dustman et al 1984, Stones & Kozma 1989). The data suggest that older individuals who exercise regularly and are fit do not demonstrate as much response slowing as do older individuals who do not exercise regularly and are not fit (Bashore 1989).

Reservations to these findings include the amount of exercise and level of cardiovascular fitness necessary for an effect on reaction time. Madden et al (1989) found no effect of exercise on older adults' response time. The authors noted that their subjects did not improve as much in fitness (measured by increase in VO2max) as other studies have reported (e.g. Dustman et al 1984).
Madden et al (1989) suggested that significant improvement in cardiovascular efficiency is a precondition to observing improvement in reaction time in older adults (Blumenthal et al 1989, 1991; Blumenthal & Madden 1988). The fact that regular exercisers show faster reaction time relative to nonexercisers also supports this conclusion (Clarkson-Smith & Hartley 1989).

In another study of exercise in older adults, Hill et al (1993) trained previously sedentary older adults in aerobic exercise and monitored mood and cognitive functioning. The exercised group experienced a 22.5% increase in VO₂max, comparable to that found by Dustman et al (1984). This suggests that the level of cardiovascular fitness was near that required for improvement in cognitive functioning. However, the large increase in cardiovascular fitness did not translate into improved cognitive functioning or a decrease in processing time. The reason for the disparate results is not immediately apparent. One possibility is that Hill et al used single measures for each cognitive ability, i.e. there was only one measure of short-term memory, the Wechsler Memory Scale Logical Memory. Also, changes in response time may have been missed because response time was not assessed directly. Another possibility is that subjects had been sedentary for at least two years prior to beginning the study. It may be that continued maintenance of fitness over the lifespan is more beneficial for alleviating the decline in speed with age, whereas once slowing has begun as part of sedentary lifestyle, this slowing may not be easily reversible by beginning an exercise regimen.

A more intriguing possibility exists within the data. Hill et al (1993) report a significant correlation between VO₂max and psychomotor speed at pretest (r = .25, p < .01; p. P15). The posttest correlations between VO₂max and psychomotor speed were not reported for either the zero-order correlation or the part correlation partialled for baseline VO₂max. However, the presence of a significant correlation indicated that an important relationship between fitness and speed existed at the time of pretest. It is unknown whether the relationship between fitness and speed changed after exercising.

Another intriguing possibility for why several investigators have been unable to find a relationship between increases in cardiovascular fitness and global reaction time or cognitive functioning involves the level of analysis of the problem. Perhaps increases in cardiovascular fitness lead to changes in cardiovascular functions that are indicative of cognitive processes, e.g. heart rate interbeat intervals (IBI), peripheral vascular activity, and blood pressure (Jennings et al 1990a,b; Lacey & Lacey 1974). Jennings et al (1990b) found significant age differences in cardiovascular responses to serial learning memory and simple reaction-time tasks. Young adults typically show increased IBI when anticipating stimuli; older adults do not show much change in IBI when anticipating stimuli. Some of these differences were due to age-related cardiovascular changes, as well as age-related changes in cognitive resource alloca-
tion. Perhaps the effects of increased cardiovascular fitness in older adults would show more clearly in psychophysiological measures of cardiac activity and therefore in the cognitive processes underlying the task-related changes in cardiac activity.

The importance of level of analysis and the conceptualization of reaction time measures is illustrated by Bunce et al (1993), who investigated the effect of age and physical fitness on reaction time and mental blocks. Blocks were operationally defined as any reaction time longer than one second on a choice reaction-time task and were thought to indicate inhibitory failures during tasks requiring sustained attention. Fitness was measured with expired volume, vital capacity, body fat, and body mass. Bunce et al (1993) found a significant Age × Fitness interaction effect on the amount of blocks, such that older, less fit subjects experienced more blocks than did older, more fit subjects. Fitness had no effect on blocks in the younger subjects and had no effect on reaction time. The authors concluded that fitness was related to the ability to inhibit extraneous information and not to reaction time, per se. However, Salthouse (1993a) conducted a reanalysis on his own data, and found that attentional blocks were not the direct cause of slowing, thus contradicting Bunce et al.

Bunce et al's (1993) line of reasoning is instructive in that the process behind the slowest reaction times was hypothesized to be inhibitory. From one point of view, fitness had an effect on the slowest reaction times, but not on all reaction times. How one conceptualizes reaction time is crucial to the understanding of the relationship of speed and age. If one asks the question of what causes slowing, one might say a breakdown in inhibitory processes. Thus, Bunce et al's (1993) conclusions can be re-formulated to suggest that fitness and age have an effect on reaction time and that slowed reaction time is the result of impaired inhibition, including slowing of inhibition.

Current data indicate that, given sufficient cardiovascular fitness, exercise is associated with improved cognitive functioning in older adults. Where the focus of improvement is, whether in reaction time, inhibitory processes, arousal, or other processes related to cardiac functions, remains to be investigated. Additional variance in age-related slowing of information processing speed has been associated with health or, as is usually the case, disease states (Dywan et al 1992, Jones et al 1991).

Houx et al (1991) conducted a study in which community dwelling subjects aged 18–63 were assessed for potential risk factors for neurological dysfunction. Risk factors included birth complications, alcohol abuse, and exposure to neurotoxins (Houx et al 1991, p. 250). Half (n = 40) of the subjects reported at least one neurological risk event and half did not. Subjects completed a version of the Sternberg memory scanning paradigm. Older subjects were significantly slowed relative to young adults and subjects in the risk group were slowed relative to the no-risk group. The authors concluded that “the existence of risk
factors for brain dysfunction aggravate the effects of aging even for subjects younger than 65 years” (p. 255). Aging combined with events associated with neurological problems result in significantly slowed information processing. Nearly 25% of the variance associated with memory scanning speed was associated with the neurological risks experienced by the subjects across the age range (Houx et al 1991). Apparently, response speed can be modulated by age, exercise (or aerobic capacity), and health. It should be noted that older adults tend to experience more events that may lead to neurological dysfunction, e.g. migraine, concussions, general anesthesia, and medication.

Other measures of brain integrity have been associated with speed of processing in older adults. Jones et al (1991) examined 100 men aged 30–80 on an impressive number of variables, from psychosocial functioning and demographic data to cognitive functioning and assessment of brain structure. In a LISREL analysis relating brain and psychosocial functions to cognitive functioning, sulci fluid volume was related significantly to the speed factor, as were education and a measure of general psychiatric symptomology. Relevant to our discussion of the relation of brain integrity to speed of response, the greater the sulci fluid volume, the slower the speed of information processing. As seen in the MRI and ERP componential analyses, brain integrity has a significant relationship to speed of response (Jones et al 1991).

The relationship between the physical health of older adults and cognitive functioning, from processing time to more complex cognitive operations, is not a simple one and is affected by many individual difference variables. Lifestyle variables have long been suspected as contributors to changes in cognition with age. It is presumed that the greater the activities of the person, the less the decline in cognitive processes. In an examination of the relationships between cognitive functioning, self-reported health, and lifestyle factors, Hultsch et al (1993) found significant correlations, albeit modest, between self-reported health and semantic processing time in a sample of normal, healthy adults aged 55–86 years. Furthermore, in older subjects, the correlation between an active lifestyle and processing speed was larger than in the relatively younger subjects. Good self-reported health and the ability to pursue an active lifestyle ameliorated some of the declines in processing speed with age. The beneficial effect of these lifestyle variables was somewhat stronger in the oldest subjects (Hultsch et al 1993).

The separable and independent effects of aging associated with disease were investigated in a multivariate cross-sectional study of older adults aged 65–91 (Anstey et al 1993). Measures of primary aging, defined as maturational processes, included reaction time, muscle strength, vibration sense, and measures of physiological vigor. Measures of secondary aging, defined as disease processes, included self-reported health, number of medications, diagnoses, and education. Subjects were assessed on both fluid and crystallized intelli-
The intercorrelation between primary aging and negative secondary aging (health) factors was 0.40.

The results showed that primary aging factors best predicted the fluid intelligence factors, but surprisingly, health factors did not predict fluid intelligence. Reaction time was the best individual predictor of the fluid factor. The authors were puzzled as to the lack of an effect of health on intelligence and speculated that their measures were not good measures of the health construct. However, allowing the health factor to covary with the primary biological aging factor may have confounded health and biological aging measures. Speed is hypothesized to be affected by health and speed, in turn, affects intelligence. Perhaps this hypothesis may help to solve the puzzle in future studies.

**Cognitive Implications of Speed of Response**

Psychologists have concentrated on defining and manipulating the cognitive processes underlying various tasks, from simple reaction time to typing skills; searching for answers to questions about the pervasive nature of slowing of behavior with age and its consequences for other, perhaps more complex processes. Here we review briefly the generalized and specific slowing hypotheses and some of the evidence for declines in working memory and inhibitory processes. Declines in working memory and inhibitory processes are also hypothesized to be a part of the fundamental changes in basic processing that in turn have consequences for more complex cognition.

**Generalized or Specific Slowing Theories**

Birren (1965, Birren et al 1980) proposed that there is a general factor of speed of the central nervous system (CNS) that is slowed with age. According to Cerella (1985), each component process is slowed and the slowing of performance of a complex task can thus be predicted from the slowing on a simple task. Further, all processes are slowed and are slowed by the same factor, in a linear fashion. The primary methodology used to support generalized slowing has been the Brinley (1965) plot of the mean of the older reaction times across tasks plotted against the mean of the younger reaction times across tasks.

Task-specific slowing hypothesizes that each task component slows at a specific rate, which may or may not be influenced to the rate of slowing of other processes. Thus, there could be slowing of the sensory-motor system that is unrelated to the slowing of more cognitive processes, slowing in the peripheral response system unrelated to central slowing, or slowing of input processes unrelated to output processes. Slowing does not affect task components in the same manner, but in each case, differential amounts of slowing can be observed.
One of the basic questions in this area is how to model generalized or specific slowing. Brinley (1965) plotted older against younger adult mean seconds per cognitive operation across two types of tasks. He found that the resulting regression equation (OLD = (1.68)YOUNG - .27) accounted for 98% ($r = .99$) of the variance in the means. Brinley concluded that response of speed of the older adult was "simple and accurately described" by the regression on the young response time (p. 131). Old reaction time was a linear function of the young response time, supporting the hypothesis of a generalized slowing across the two tasks.

Cerella’s (1985) excellent meta-analysis of young and older adults’ reaction times using Brinley plots provided impressive support for the generalized slowing model of reaction time. Cerella (1985) plotted 189 old-young pairs of mean reaction times taken from 18 studies, across 189 task conditions, and found that a general slowing coefficient explained much of the variance in the means. Cerella added one factor to a strong generalized slowing hypothesis. His meta-analysis indicated that there may be a peripheral slowing component and a central slowing component. The size of the slowing coefficient depended on the ratio of peripheral and central processes involved in task performance. How much slowing is observed in the performance of any one task depends on the mix of sensory-motor and central processes, but a general slowing factor affects age-related differences in reaction time performance.

Cerella (1991) stated, “The evidence is near-to-overwhelming that age is experienced, at least to a first approximation, as some sort of generalized slowing throughout the central nervous system, manifested equally in any task that requires the processing of information” (p. 220). Anyone viewing a Brinley plot is sure to be impressed by the regularity of the data points and the amount of variance for which the straight line regression accounts.

Myerson and his colleagues, with minor changes to incorporate a nonlinear factor, also demonstrated the all-pervasive quality of age-related slowing (Hale et al 1987, Lima et al 1991, Myerson et al 1990). They approached modeling age-related changes in response time with the common assumption that mean data from young and older subjects can be plotted without regard to task, underlying distributions of response times, homogeneity of variance, or internal task parameters (such as speed-accuracy tradeoffs), all of which may affect mean response times.

Questions have been raised about the use of Brinley plots to model generalized slowing, usually in the context of an argument in favor of task-specific slowing (Amrhein & Theios 1993, Fisk et al 1992, Laver & Burke 1993, Mayr & Kliegl 1993, Sliwinski et al 1994). Fisk et al (1992) demonstrated that Brinley plots were insensitive for discriminating between a pattern of means that indicated the general slowing model and a pattern of means that indicated the task-specific slowing model. This was especially the case when there was a
complete overlap in the mean response times in the younger sample. In addition, because of the dependence of $r$ on the range of data points, the percentage of explained variance is a poor measure of how well a linear model fits the data (see also Cohen & Cohen 1983). Thus, although an $r$ of .98 looks large, it may be spuriously inflated by the selection of data points to include in the model (Fisk et al 1992).

Sliwinski et al (1994) pointed to a related weakness of Brinley plots that has been largely ignored in the aging literature, that is, the dependence of the plot on mean data. Group means are not sufficient for a thorough test of the generalized slowing model. Theoretically, the real question is not, on the average, are older adults slowed, but rather: Is any one older adult slowed across tasks? Furthermore, the size of a mean is completely determined by the number of subjects and the distribution of scores. A mean may not be representative of the distribution from which it was calculated (for an extensive review of this issue, see Wilcox 1987).

In an elegant set of analyses, Sliwinski et al (1994) examined the relationship of young and older subjects' distributions of the time taken to add numbers together. An analysis of distributions showed that the amount of slowing was similar for the extreme ends of the older subjects' distribution, i.e. the fastest and slowest subjects were slowed in the same fashion. Older adults slowed differentially depending on the task subcomponents. Initiating addition caused greater slowing than did incrementing the size of the integer to be added. The results were compatible both with a general slowing factor and with task-specific slowing factors (Sliwinski et al 1994).

Another cited weakness of Brinley plots is that they combine reaction time means without regard to the task or specific experimental manipulation. One could also argue that this is the strength of the plots, that the slowing is task independent. However, an essential assumption of regression analysis is adequate sampling of subjects within the population (Cohen & Cohen 1983). Brinley plot "subjects" are tasks and the tasks chosen may differ in important respects from one another and may not be homogenous or regularly distributed as assumed. Careful attention to incrementally changing task parameters and a demonstration that the tasks are representative of the population from which they come are essential for fulfilling the assumptions of regression analysis.

Mayr & Kliegl (1993) addressed the problem of task selection by increasing the number of task components to be performed by the subjects, thus manipulating the amount of task complexity. The authors were interested in age-related effects on working memory, but it is their analyses of slowing that concern us here. When young mean latencies were plotted against old mean latencies, two regression lines best fit the data, based on the type of task. They found two functions that described the slowing: both general across subjects,
yet specific to the tasks. Furthermore, Mayr & Kliegl (1993) concluded that information processing itself is not a static set of steps encountered in a linear fashion, but rather is “a dynamic switching in working memory” of task processes (p. 1317). These results are compatible with a hierarchical notion of the effects of slowing, in that universal slowing of processing is mediated through higher-order components, such as working memory, and may be evidenced in performance differences by task.

**Speed and Knowledge as Task Parameters**

Salthouse (1982, 1985, 1988, 1991, 1993b) has been at the forefront of theoretical and methodological innovations in the study of age-related changes in speed and the relationship of those changes to cognition. His summaries of the field have been precise and exhaustive, while pointing to new questions. In one of the most interesting contributions to our understanding of generalized and specific slowing issues, Salthouse (1993a) proposed that tasks differ primarily in terms of speed and knowledge requirements of the task. According to Salthouse, “If successful performance is primarily dependent on speed, then the age effects can be expected to be quite large…. If knowledge is an important aspect of the task, as in most of the…verbal tasks…, then the age effects can be expected to be much smaller… (p. P34).

Salthouse (1993a) based his conclusion regarding the relative contributions of knowledge and speed to age-related differences on the results of two studies of young and older adults. Subjects were assessed on a variety of personal characteristics, e.g. education, self-reported health, and amount of time spent reading books and working word puzzles. The subjects completed motor speed, digit symbol, and several word-knowledge tasks (e.g. unscrambling anagrams). Salthouse found that older adults showed small differences from young adults on the tasks dependent on word knowledge and larger differences on tasks more independent of word knowledge.

Placing tasks on a speed-knowledge continuum is an extremely important step forward. The promise of such a continuum is that, given a careful analysis of task components, one would be able to predict the magnitude of age differences in performance. Conversely, one could reason from the pattern of age differences on performance to the relative amounts of knowledge and speed inherent in the task. No longer need attention be paid to formulating the parameters of generalized slowing, but rather to the requirements of the task, to the processes and representations underlying performance.

**Speed of Cognitive Processing**

Salthouse’s conclusions can be supported by data from a number of areas, from the study of intellectual abilities to visual processes. In fact, the distinction between knowledge and speed is reminiscent of the Horn-Cattell fluid-
crystallized intelligence distinction in intellectual abilities (discussed below). In this section, we review some studies that appear to support the speed-knowledge continuum. An outgrowth of examining studies that show a reduction in the effect of age-related slowing of response time on task performance is the consideration of other hypotheses for specific declines in performance with age. A review of the age-related changes in working memory, inhibitory processes, and internal noise concludes this section.

Studies of the speed of lexical activation rarely have found age differences between young and older adults, which would be expected if slowing affected all cognitive processes equivalently (e.g. Howard 1988, Howard et al 1986, Madden 1988). In a meta-analysis of lexical decision studies, Lima et al (1991) found that, indeed, older adults were slower to determine whether or not a string of letters was a word. However, the degree of slowing in a lexical task was not as great as would have been predicted on the basis of slowing in nonlexical decision task performance. Generalized versus specific slowing is not the issue according to Lima et al. The authors state that the critical distinction among tasks is the lexical-nonlexical distinction and that research should be directed to understanding what components differ between these types of tasks (see also Laver & Burke 1993).

In an analysis of visual word identification, Madden and his colleagues have conducted a series of studies to indicate that there are age-related speed-knowledge processing differences in specific subcomponents of word-identification task performance (Allen et al 1993; Madden 1992; Madden et al 1992, 1993). For example, Madden (1992) administered a primed lexical decision task to subjects aged 20–78, who had to indicate whether or not the target letter string was a word. Across age, mean reaction time to the targets was slowed; however, the amount of facilitation for related primes was consistent across age. Madden concluded that although slowing of response time was a factor in task performance, there were task components that did not show age-related declines. Specifically, those processes after the initial perceptual processing (e.g. more knowledge-based processes), showed little or no age-related declines in speed (Madden 1992).

Several studies of arithmetic tasks have shown similar dichotomies in age-related performance differences (Allen et al 1992, Geary et al 1993, Geary & Wiley 1991). For example, Geary et al (1993) tested young and older adults on simple and complex subtraction tasks. Older subjects showed a higher level of subtraction strategies relative to those of younger adults and, in complex subtraction, were quicker to execute the borrow function than were young adults. These functions seem to be more dependent on prior knowledge and thus insensitive to age-related changes in speed of processing (Geary et al 1993).
Alternative Explanations

Working memory, inhibitory processes, and internal noise are among the theories used to explain age-related differences in cognitive performance (Allen 1991, McDowd 1994, Salthouse 1991). Within an hierarchical theory of cognition, a notion of generalized slowing and these alternative explanations need not be mutually exclusive. In complex cognitive processing, the contributions of inhibition and working memory may be greater than the contribution of generalized slowing. If, on a particular task, working memory declines and is highly associated with performance differences, it does not negate the contribution of generalized slowing. It indicates that, for that particular task, decline in working memory is the appropriate level at which to make causal inferences. Generalized slowing need not be limited to facilitation, but may influence inhibition and, ultimately, working memory. In solving tasks, a subject needs to keep in mind intentions as well as elements to be combined in a complex response. Attention and working memory are dissipative processes and it seems reasonable that speed of input and output will influence the effectiveness of these functions with age. Understanding how such efforts might be manifest in cognitive performance requires more complex research designs than have previously been used.

In the case of internal noise, slowed neural processing speed may cause incoming stimuli to be represented in a number of different ways. The representation of stimuli will “oscillate” (Allen 1991), causing an increase in internal noise and declines in cognitive processing.

Speed and Intelligence

A hierarchical model of the effects of response speed would predict that individual differences in speed of processing is associated significantly with individual differences in complex cognitive functioning or intellectual ability. The issue is not that processing speed is related to intellectual abilities, but rather is how age-related slowing affects intellectual ability performance. Studies investigating this issue have been primarily correlational and cross-sectional in nature. However, a number of studies have examined longitudinal changes as well. The evidence from these studies supports the evidence from studies of cognitive processing, i.e. age-related slowing in basic processes accounts for much of the variance in a general decline of intellectual abilities.

A few issues need mentioning before reviewing the data. One is that measures of speed of response tend to be different from those in the information processing tradition. This reduces the comparability of perceptual difficulty studies, psychometric studies, and information processing studies. Another is that longitudinal changes in speed have been smaller than cross-sectional
studies have suggested. Finally, because of the correlational nature of many of the studies, conclusions about associations and relationships can be made, but more mechanistic conclusions cannot be drawn.

Several psychometric studies have attempted to determine whether there is one general speed factor or several speed factors that change with age (see Cunningham & Tomer 1990, White & Cunningham 1987). Information processing theorists have spent much time examining this issue. Two studies (Hertzog et al 1987, White & Cunningham 1987) report more than one factor that could be called speed factors. This accords well with cognitive literature, i.e. there appear to be task-specific speed-of-response influences. However, in factor analysis, which allows for hierarchical examination of factors, one could examine whether the first-order factor intercorrelates can be subsumed under a second-order factor.

Tomer & Cunningham (1993) investigated the first- and second-order speed factors for performance on five categories of speed tasks (symbolic perceptual speed, figural perceptual speed, choice reaction time, Sternberg reaction times, and card-sorting speed) in 296 subjects (young: 18–33 years of age, old: 58–73 years of age). The first-order factor analysis resulted in a five-factor model fitting the a priori categories of speed tasks. The five speeds were allowed to correlate with one another and the intercorrelations were from .41 to .84. A second-order factor solution accounted for as much variance as the first-order five-factor model, but did not improve the overall fit of the model to the data. The second-order factors were also allowed to intercorrelate and the correlations range from .6 to .8. Tomer & Cunningham (1993) concluded that a one- or even two-factor model of speed did not fit the data, but that at least five factors were needed to describe the data. The authors stated that “higher order analyses of the structure of intellectual speed do not seem very promising...” (p. 21). Tomer & Cunningham do not interpret the high intercorrelations among the second-order factors; the general speed factor may be hidden among the intercorrelations. Thus, Tomer & Cunningham appear to have established a multifactor model of speed; however, an analysis of factor structure only indirectly addresses the question of whether general processes underlie slowing of response speed with age.

One of the defining notions of age-related changes in intellectual abilities today has been the distinction between fluid and crystallized intelligence. Horn (1982) presented data to indicate that fluid intelligence tended to decline with age, was associated with slowing of response speed, and may be more associated with biological factors in aging. Crystallized intelligence, in contrast, tended to increase with age and was less associated with slowing and biological factors. However, Horn (1982) was careful to point out that the data led him to conclude that slowing may be a consequence and not a cause of declines in intellectual ability.
Further psychometric support for the speed-knowledge dichotomy comes from Schaie & Willis (1993), who examined patterns of age differences in intellectual abilities in 1628 subjects. Measures of intellectual ability included inductive reasoning, spatial orientation, numeric and verbal ability, perceptual speed, and verbal memory. Perceptual speed declined across cohorts, with the oldest cohort slowing at about half the rate of the youngest cohorts. Schaie & Willis found that the pattern of age differences varied according to the degree to which the measure depended on speed or knowledge. Those measures dependent on speed tended to decline with age, whereas those dependent on knowledge tended to remain stable across age (Schaie & Willis 1993, Schaie 1989).

According to Hertzog (1989), part of the unexplained variance in age changes in intellectual functioning may be the result of “performance-specific influences of information-processing speed” (p. P645). Hertzog observed significant correlations of speed with Primary Mental Ability (PMA) subtests in a cross-sectional study of adults aged 43–78. Furthermore, a measure of the speed to fill in the PMA answer sheet accounted for some of the differences in intellectual abilities. Hertzog (1989) argued for a “both-and” approach to speed and intellectual abilities. In other words, there is a general negative effect of slowing on intellectual abilities with age and a specific negative effect of slowing.

Support for the hypothesis that there are general and specific effects of speed on intellectual abilities comes from two studies, one cross-sectional and the other longitudinal, of various cognitive tasks across age groups (Hultsch et al 1990, 1992). The cross-sectional study (Hultsch et al 1990) indicated that working memory, in addition to speed of processing, was associated significantly with individual differences in memory performance. Hultsch et al extended the previous studies of speed and complex cognitive functioning by including two measures of working memory. Working memory accounted for differences in complex memory abilities above and beyond speed and no other basic information process or task-specific process accounted for more variance. Perhaps working memory is Schaie’s missing component to explain differences in intellectual ability with age.

Hultsch et al’s (1992) longitudinal replication supported, for the most part, the cross-sectional findings. However, the longitudinal results revealed a decline in cognitive functioning over the three years of the study that was unrelated to speed and working memory performance. Working memory declined over time even when speed was partialled out of the scores. When the general effects of speed were statistically equated, working memory and other cognitive processes declined, and the decline was unrelated to speed (Hultsch et al 1992).
Lindenberger et al (1993) addressed the question of whether the relationship of speed and intellectual abilities holds within the oldest-old population. Subjects aged 70-103 were assessed on speed, reasoning, memory, knowledge, and word fluency tasks. In a structural equation analysis, the statistical model that associated a general speed factor with intellectual abilities fit the pattern of data well. Allowing speed to affect individual intellectual abilities independently (as in the specific slowing model) did not fit the data. Thus, in the oldest-old, declines in speed of response mediated differences in intellectual abilities. Furthermore, the pervasive nature of the effect of speed was observed in the increased size of intercorrelations among intellectual abilities.

In summary, slowing in speed of response with age underlies much of the decline in intellectual ability with age. The degree to which the effect of speed is observed on performance is the result of the relative amounts of knowledge and speed required for successful task completion. Other studies point to working memory as a significant factor in age-related intellectual ability declines that are not accounted for by speed.

Discussion

This review of the literature on age-related slowing of behavior has examined several thoughts about theory production. One is that the psychology of aging is an interface for many of the psychological conceptions about the organization of behavior. This interface promises gains in understanding as we use our ideas about aging to test our ideas about behavioral organization, and vice versa. Luce (1986) made several relevant observations in his comprehensive survey of response times. He stated that "response time is psychology's ubiquitous dependent variable" (p. 6). The use of response time to investigate behavior assumes that the processing of information is highly structured and different paths through that structure should entail different response times. This represents the traditional experimental design to make inferences from the pattern of response times obtained under different conditions in relation to hypothesized cognitive structures (Luce 1986). Several points relevant for aging research might be added to Luce's thinking on this subject. First, if the structure of the information pathways in the brain is altered because of learning, disease, or aging, then one might also find response-time differences. Changes with age in response time can help to validate our theoretical structures about how cognition is organized. Second, although psychology generally has used response time as a dependent variable, in aging studies, response time can be viewed as an independent variable, as that which is used in explanations.

Third, chronological age is seen increasingly as a "fickle mistress," in that the use of age as a variable should be an initial point of departure to be supplemented and, possibly, to be replaced by other variables. Chronological
age is only an index of the passing of time, and correlations with age may be positive or negative; large, small, or zero; and linear or curvilinear. One method for replacing age comes from biological research on aging. In biology, the concept of markers has been used to refer to measures of the status of an organism, other than age alone. Birren & Fisher (1992) discussed criteria that might be used to test the validity of behavioral markers of aging. An example of a behavioral marker is slowing of reaction time. One of the suggested criteria against which to test the significance of slowing is length of life. That is, measures of slowing take on a greater significance if individuals who show the greatest slowing are also the shortest lived. It remains to be demonstrated whether the degree of slowing predicts the remaining years of life. Another criterion is gender differences, as women tend to live longer than men. There may well be identifiable correlates of differences in male and female longevity.

Heikkinen (1994) suggested another useful way to model age-related changes. After reviewing epidemiological and ecological models of aging, Heikkinen proposed the model of an “effective causal complex” (ECC) to represent clusters or groups of factors that may affect patterns of age-related change. Adding ECCs to psychological research allows the examination of functional capacity, length of life, and morbidity in relation to behavioral outcomes. One way to enlarge our scope of ECCs is to examine contemporary models of aging held within the biological, behavioral, and social sciences. While biological scientists study the destructive processes associated with the passage of time, social scientists are interested in the changing course of life in such areas as social roles, achievement, and self-esteem (Marshall 1995).

Yates & Benton (1995) offer the concept of homeodynamics as a useful metaphor to encourage the integration of theory in aging. They distinguish aging from senescence, the latter referring to the degradation of living systems embracing damage, harm, loss, or failure. For psychology, the significance of Yates & Benton lies in the fact that much of the research on aging deals with information and constructive processes that may exist concurrently with the destruction of the multicellular, self-organizing systems. Schroots (1995) discussed the implications for psychology of the notion that entropy is not merely a downward slide toward disorganization; in contrast, order and disorder may emerge over time. Schroots leads again to Heikkinen’s causal complexes. Thus, slowness seems to be more closely linked with the biological complex of variables, and crystallized intelligence or knowledge seems to be more closely linked with external factors, such as social structures. These links among causal complexes may replace the imprecision associated with the use of age as our principal index of aging.
SUMMARY AND CONCLUSIONS

Over 100 years of observations have established that slowness of behavior is a characteristic of becoming old, although it is now recognized that health, use of medications, and physical activity may modify the extent of the slowing. Early research indicated that there is a limited contribution to slowing by peripheral sensory-motor factors. Substantial evidence has pointed to the central nervous system as the locus of the slowing.

Recent investigators have expressed divided opinions about whether there is a pervasive general slowing of behavior by the central nervous system or whether there are specific localized mechanisms. This is not unlike early disputed views of the brain as having localized or global behavioral functions: Both principles appear to be simultaneously true. Sufficient research has been conducted to indicate that there are specific factors as well as a general process associated with the slowing of behavior with advancing age. Whether such slowing is a primary or secondary cause of age differences in cognitive processes is a significant scientific issue.

A marked broadening of research on aging has been accompanied by an interest in identifying both the neurophysiological correlates of slowing as well as its role in specific cognitive processes. Yet another aspect of the changing research picture is the trend to move beyond the mere use of chronological age as the sole basis for comparing performance differences. Measurement of more independent variables is suggested as part of clusters or causal complexes that will indicate sources of the changes in speed and other aspects of behavior. These causal complexes include biological indicators such as disease, physiological capacity for work, and length of life, as well as causal complexes of social factors involving such variables as education, occupation, and ethnicity.

There has been considerable discussion of markers of aging. In this approach, factors found to be closely associated with advancing age are used as measures of the effectiveness of attempts to modify the course of aging, e.g. by diet, exercise, new learning, and drugs. Along with other biomarkers of aging, speed of behavior may prove to be a criterion for assessing the impact of interventions on the rate and processes of aging. As a marker of aging, speed needs further exploration that will compare the slowness observed in different subgroups of adults with a wide range of outcomes in their productivity, capacity for adaptation to life’s demands, and health.

The present status of information about slowness of behavior with advancing age indicates that it is one of the most reliable features of human life. Its origins remain to be understood in greater detail, as well as its consequences for the well-being of the individual. Research, both longitudinal and experi-
mental, is needed to deepen our understanding of slowing of mediation by the central nervous system and its consequences for complex behaviors.

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