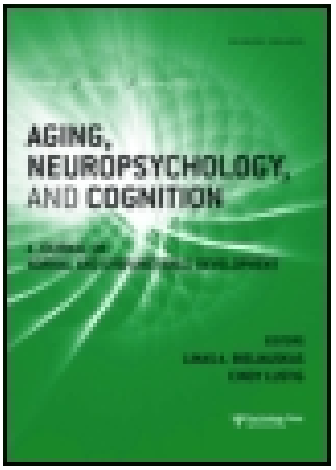

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The Neural Noise Hypothesis: Evidence from Processing Speed in Adults with Multiple Sclerosis*

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ABSTRACT

On measures of speeded performance, adults with multiple sclerosis (MS) typically respond more slowly than do adults without MS. A review of 12 published studies yielded 38 pairs of response times (RTs) in which each pair consisted of a mean RT for a sample of persons with MS for an experimental condition and the corresponding mean RT for a sample of persons without MS. The primary result was that, across the 38 conditions, RTs for individuals with MS increased linearly as a function of RTs for persons without MS. Because MS involves demyelination of the axons in the central nervous system (CNS), it is suggested that this result provides support for the neural noise hypothesis of cognitive aging.

Speed of information processing increases throughout childhood and adolescence, reaching a peak in young adulthood; thereafter, speed declines, gradually during middle age but more rapidly during old age (Kail & Salthouse, 1994). For example, on many tasks, the mean response time (RT) for 10-year-olds is approximately 2.5 standard deviations greater than the young adult mean; the mean response time for 60-year-olds is approximately 2 standard deviations greater than the young adult mean. (In both cases, the standard deviations are for young adults.)

The consistent pattern of developmental change in speed of processing suggests that the underlying mechanism is general, rather than linked to specific tasks. That is, some global mechanism that changes with age limits the speed with which individuals can respond on most tasks. In fact, considerable evidence provides support for the hypothesized global mechanism. For example, if two measures of speeded performance reflect a common age-related mechanism, then statistical control of the variance in one measure should greatly reduce the age-related variance in the other. In fact, correlations between age and speeds of many cognitive processes are attenuated substantially when performance on a paper-and-pencil measure of processing speed (e.g., the Digit Symbol Substitution task from the Wechsler Adult Intelligence Scale [WAIS]) is partialled out. This suggests that the different speeded tasks are tapping a common construct (Kail & Salthouse, 1994).

Many theorists have proposed that this global pattern of development might reflect fundamental neural changes. Specifically, according to the *neural noise hypothesis*, the signal-to-noise ratio within the central nervous system (CNS) changes across the life span (Crossman & Szafran, 1956; Welford, 1956). This hypothesis is based on the assumptions that information is transmitted within the CNS in varying degrees of fidelity or *strength* and that these transmissions take place against a backdrop of random

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neural activity or *noise*. The faster information processing associated with late childhood and adolescence might reflect either a stronger signal or less background noise; the slower information processing associated with aging might reflect either a weaker signal or more background noise.

The basic ideas associated with the neural noise hypothesis have been included in a number of specific models. For example, Myerson, Hale, Wagstaff, Poon, and Smith (1990) proposed an information-loss model to explain age-related slowing of cognitive processes. In their model, processing occurs in discrete steps and some information is lost at each step between input and response. The greater the information loss, the longer a processing unit must wait for sufficient information to accrue to identify a signal. Older adults are presumed to lose more information per step than younger adults, which leads to the prediction that older adults' RTs should increase as a function of younger adults' RTs. In fact, this is a common result (Cerella & Hale, 1994; Myerson et al., 1990).

Many age-related changes in the CNS are consistent with the general neural noise hypothesis and its specific variants. For example, many transient connections in the CNS are eliminated during childhood (Huttenlocher, 1979), which could increase signal strength and decrease background noise. Similarly, levels of neurotransmitters decline during aging (Rogers & Bloom, 1985), which could decrease signal strength.

In addition to these anatomical findings, there is a small amount of relevant theoretical and experimental work. One line of research involves neural network modeling in which the goal is to determine whether neural change like that proposed in the neural noise hypothesis results in the predicted pattern of age-related change in processing speed (Cerella, 1990; Cerella & Hale, 1994; Salthouse, 1988). Another relevant line of investigation involves attempting to mimic the impact of neural noise by showing the impact of degraded stimuli on young and older adults' performance (e.g., Cremer & Zeef, 1987). Both of these approaches have produced evidence that is consistent with the neural noise hypothesis. Nevertheless, the evidence is far from compelling because it is indirect and scanty.

The aim of the research described here was to take a different approach to evaluating the neural noise hypothesis. The starting point of the present work was the assertion of the neural noise hypothesis that a degenerating nervous system in older adults leads to a diminished signal-to-noise ratio, which yields slower responding. Of course, the integrity of the CNS is affected by many variables other than age; diseases and environmental hazards also can impair neural functioning. Consequently, individuals who have suffered CNS damage due to disease or environmental hazard may provide insights into the neural noise hypothesis. To illustrate how their data can be useful, consider the rationale underlying the use of Brinley plots (Brinley, 1965). Assume that young adults' responses on a task consist of several processes, such that their total time to respond, RT_Y, can be defined as

$$RT_Y = a + b + c..., \quad (1)$$

where a is the time to execute process A, b is the time to execute process B, and the like. If older adults execute each of these processes more slowly, by a constant amount, then their time to respond, RT_O, would be

$$RT_O = ma + mb + mc..., \quad (2)$$

where a, b, and c are defined as before, and m is the factor by which older adults respond more slowly than younger adults. Rewriting Equation (2) so that RTs for older adults are expressed as a function of RTs for younger adults (and ignoring any additive constants) yields

$$RT_O = mRT_Y. \quad (3)$$

According to Equation 3, RTs for older adults are simply a multiple of RTs for younger adults. Consequently, across different experimental conditions that produce a range of RTs for younger adults, RTs for older adults should increase linearly as a function of younger adults' RTs,

with a slope of $m > 1$. In fact, the predicted outcome has been obtained in several studies (Kail & Salthouse, 1994).

This same logic can be readily extended to study RTs in adults who have suffered CNS damage due to disease or environmental hazard. Specifically, in comparison to adults who have not suffered CNS damage, adults with a damaged CNS should have a diminished signal-to-noise ratio, which should produce slower responding. Expressed in terms of Equations (1) – (3), if response time for adults with an intact CNS, RT_I, is defined as

$$RT_I = a + b + c.... \quad (4)$$

then response time for adults with a damaged CNS, RT_D, would be

$$RT_D = ma + mb + mc.... \quad (5)$$

Rewriting Equation (5) so that RTs for adults with CNS damage are expressed as a function of RTs for adults with an intact CNS yields

$$RT_D = mRT_I. \quad (6)$$

Thus, across different experimental conditions, RTs for adults with CNS damage should increase linearly as a function of RTs for adults with an intact CNS and the slope of this function, m, should be greater than 1.

In the work described here, the focus was speed of processing by adults with multiple sclerosis (MS), a disease of the CNS in which axons become demyelinated. Symptoms of the disease, which include inflammation of nerves in the eye, fatigue, and clumsiness in the limbs, typically first appear in young adulthood (i.e., among 20- and 30-year-olds). Two features make it a potentially useful tool for investigating the neural noise hypothesis. One feature is that, although the neural damage associated with MS is not completely understood and varies considerably across individuals, at least three changes occur that could produce effects like those associated with the neural noise hypothesis. First, demyelinated neurons transmit information more slowly. Second, demyelination results in plaques, which can disrupt neural transmission. Third, as the disease progresses, demyelinated axons degenerate and are no longer capable of transmitting information.

The second relevant feature of MS is that individuals with the disorder are often impaired in attention, short-term memory, abstract reasoning, and information processing speed but not in language (Rao, Leo, Bernardin, & Unverzagt, 1991). More generally, the cognitive profile for MS is very similar to findings with older adults in which fluid intelligence is more influenced by aging than is crystallized intelligence (Horn & Hofer, 1992).

Thus, the specific aim of the project was to determine if RTs for adults with MS are well described by Equation 6. That is, can RTs for adults with MS be expressed simply as a multiple of RTs for individuals without MS? To answer this question, data were obtained from studies published previously. Archival data are particularly well suited for the present project because they encompass a wider range of tasks than typically would be included in a single experimental study. They thereby provide a more rigorous test of the extent to which Equation 6 characterizes across-task variation in RTs for adults with CNS damage.

METHOD AND RESULTS

To obtain data for the present analyses, PsycLit and MedLine were searched using *multiple sclerosis*, *cognition*, and *reaction time* as the key words. From the articles that were retrieved, two criteria were used to select articles for analysis. First, a study had to include a sample of individuals with MS and a sample of individuals without MS who were matched on chronological age. Second, RTs had to be reported and these had to be collected under instructions that, explicitly or implicitly, encouraged subjects to respond rapidly.

The search yielded 12 studies that met these criteria (see Table 1). The 12 samples in these studies were reasonably homogeneous in terms of age, with mean ages of the samples of adults with MS ranging from 33.2 to 48.7 years. Several studies included more than one group of adults with MS. In the initial analyses, their results were combined to create a single mean RT for adults with MS.

Table 1. Studies Included in the Analyses of Individuals with Multiple Sclerosis (MS).

Study	CA	Number of conditions	Task
Arena et al. (1986)	33.2	2	Simple RT
Beatty et al. (1988)	48.7	2	Word production; coding
Beatty & Monson (1994)	47.0	2	Word production; pegboard
Giesser et al. (1992)	36.5	2	Recognition RT
Grigsby et al. (1994)	39.0	2	Alphanumeric sequencing; articulation
Heaton et al. (1985)	37.4	2	Trail making A & B
Kujala et al. (1994)	43.3	8	Naming; simple & choice RT; motor tasks
Litvan et al. (1988)	36.3	10	Pegboard; simple RT; writing; recognition RT
Rao et al. (1989)	44.4	3	Recognition RT
Rao et al. (1991)	45.7	2	Stroop task; simple RT
Ron et al. (1991)	38.3	1	Letter counting
Ryan et al. (1993)	35.8	2	Trail making; word fluency

Note. RT = response time; CA refers to the mean chronological age of the sample of adults with MS. Because adults without MS were matched by age, their mean CA is very similar to the value listed for adults with MS.

The 12 studies in Table 1 included a total of 38 pairs of mean RTs. That is, each case in the data set consisted of a mean RT for one of the 38 conditions listed in Table 1 from persons with MS along with the mean RT for that same condition from persons without MS. In the initial analysis, all 38 pairs of mean RTs were fitted to Equation 6. The fit was excellent, with $R^2 = 0.993$ and $m = 1.36$. That is, as shown in the left panel of Figure 1, on tasks that included counting letters, simple RT, moving pegs, and naming pictures, adults with MS tended to take about 36% more time to respond than did adults without MS.

The data included many pairs in which both RTs were less than 500 ms as well as some pairs in which both RTs exceeded 20 s. Because of the possibility that a few very large RTs were distorting the results, the analyses were repeated using only

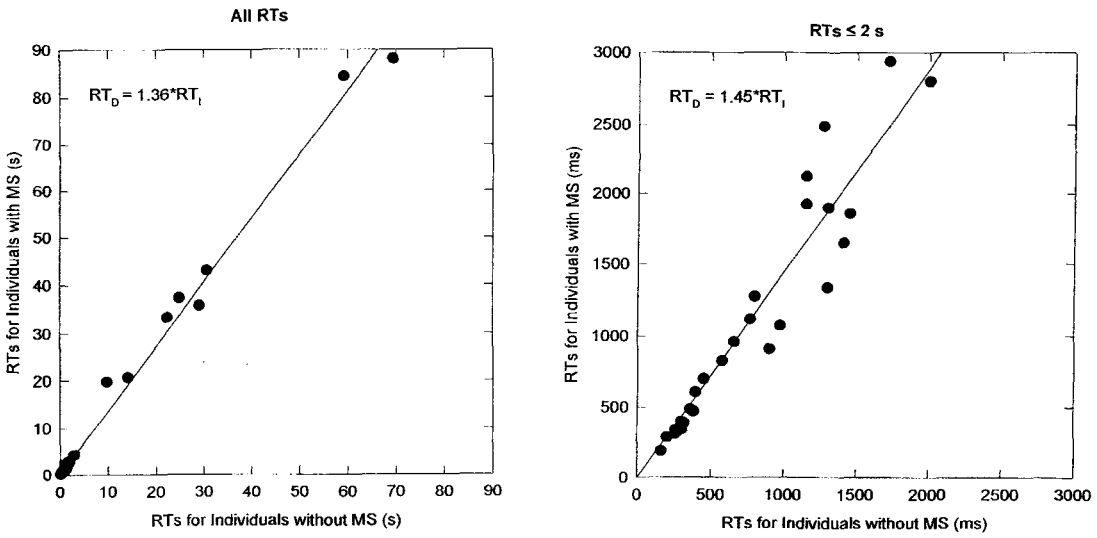

Fig. 1. Each point represents the mean response time (RT) of a sample of adults with multiple sclerosis (MS) from one of the studies listed in Table 1 and the mean RT for the corresponding sample of adults without MS. Also shown is the best fitting linear function derived from Equation 6. The left panel depicts all 38 RTs; the right panel shows the 28 RTs in which, for adults without MS, the mean RT ≤ 2 s.

pairs in which the mean RT for adults without MS was less than or equal to 2s. This criterion was somewhat arbitrary but was selected because, for RTs on nonlexical tasks, the function relating younger and older RTs may become curvilinear beyond approximately 2s (Lima, Hale, & Myerson, 1991). The resulting 28 pairs of RTs were also fitted to Equation 6. As shown in the right panel of Figure 1, the fit remained excellent, with R^2 = 0.966, and m = 1.45. Thus, as predicted by Equation 6, and consistent with the neural noise hypothesis, RTs for adults with MS were slower, by a constant multiple, than RTs for adults without MS.

Additional evidence was provided by analyses that examined samples that differed in the severity of MS symptoms. Of the studies listed in Table 1, five included two groups of adults with MS. In each case, one group was more impaired than the other; unfortunately, impairment was not defined consistently across the five studies. Some characteristics of the two groups are shown in Table 2. Individuals with more severe impairment tended be to somewhat older, and had been ill longer. Also, they had higher scores on the Kurtzke Expanded Disability Status Scale (EDSS; Kurtzke, 1983), where higher scores indicate greater disability. However, studies within each category (i.e., less and greater impairment) are far from homogeneous. For example, the "cognitively intact" patients in the Beatty et al. (1988) study had had MS longer and had greater EDSS scores than the "demented" patients in the Giesser et al. (1992) study and the "mildly deteriorated" patients in the Kujala et al. (1994) study.

This heterogeneity notwithstanding, Equation 6 was fitted separately to the RTs of groups with less and more severe impairment associated with MS. Each group's data was fitted twice, once using all 16 pairs of mean RTs, and once using only the 13 pairs in which the mean RT for individuals without MS was 2s or less. In all cases, the fit to Equation 6 was excellent, R^2s $\geq$ 0.982. Furthermore, as shown in Figure 2, the estimated value of m was greater for adults with more severe MS than for adults with less severe MS. Thus, using the m values obtained from the analyses in which samples of adults without MS had mean RTs $\leq$ 2s (because these estimates are less influenced by outlying RTs), adults with less severe MS symptoms take roughly one third again as much time to respond as adults without MS whereas adults with more severe MS symptoms take almost twice as much time to respond.

A final analysis also provides converging evidence. Of the seven studies in which adults with MS were not differentiated by the severity of their symptoms, five provided EDSS scores. In four of these five studies (Litvan et al., 1988; Rao et al., 1988; Rao et al., 1991; Ryan et al., 1993), the mean EDSS value ranged from 1.9 to 4.3, a range similar to the samples in Table 2 with less severe MS symptoms. In the fifth study, by Grigsby et al. (1994) the mean EDSS score was 5.1, a value common to both the more and less severe groups in Table 2. Because the subjects in the aforementioned four studies have EDSS scores like those of the less severe samples in Table 2, their RTs should also resemble those of samples of less severe MS adults from Table 2. In fact, these 17 pairs of RTs, which are depicted as open circles in the two panels of Figure 2, are well described by Equation 6 with m = 1.14 (for all RTs) and m = 1.32 (for RTs $\leq$ 2s). That is, as would be expected if these individuals are typical of those with less severe MS symptoms, their responses were about one third again slower than those of adults without MS.

DISCUSSION

The primary result of the present work is that, across a variety of different tasks and experimental conditions, RTs for individuals with MS increased linearly as a function of RTs for individuals without MS. Furthermore, when the samples of individuals with MS were grouped according to the severity of their symptoms, RTs for individuals with more severe MS symptoms increased more rapidly than RTs for individuals with less severe MS symptoms. In the remainder of this section, I first discuss some limiting conditions on these results, and then consider their implications for the neural noise hypothesis and for the nature of cognitive deficits associated with MS.

Limiting Conditions

One important limiting condition associated with these results is that they were based on group means, not on individuals' RTs. Because group means do not always reflect performance patterns for individuals, it is important to replicate these results with research in which RTs are measured for individuals. Second, as described earlier, the samples varied considerably in terms of the age of the participants, the severity of

Table 2. Characteristics of Individuals in Samples with More and Less Severe Symptoms of Multiple Sclerosis (MS).

	Group with less severe symptoms				Group with more severe symptoms			
Study	Name	CA	EDSS score	Disease duration	Name	CA	EDSS score	Disease duration
Arena et al. (1986)	Probable MS	29.4	——	——	Definite MS	37.0	——	——
Beatty et al. (1988)	Cognitively intact	48.8	6.5	19.4	Cognitively impaired	48.6	7.3	14.9
Giesser et al. (1992)	Nondemented	34.0	3.7	8.0	Demented	39.0	5.9	11.1
Heaton et al. (1985)[a]	Relapse-remitting	——	——	——	Chronic-progressive	——	——	——
Kujala et al. (1994)	Preserved	43.3	5.0	8.7	Mildly deteriorated	43.3	5.5	8.7

Note. CA = mean chronological age; EDSS = Expanded Disability Status Scale.

[a]Means for age, EDSS score, and disease duration for the entire sample of adults with MS were 37.4, 3.10, and 9.4, respectively, but were not reported separately for the two samples of adults with MS. However, Heaton et al. reported that the chronic-progressive group was significantly older, had greater disability assessed by the EDSS, and had been ill longer.

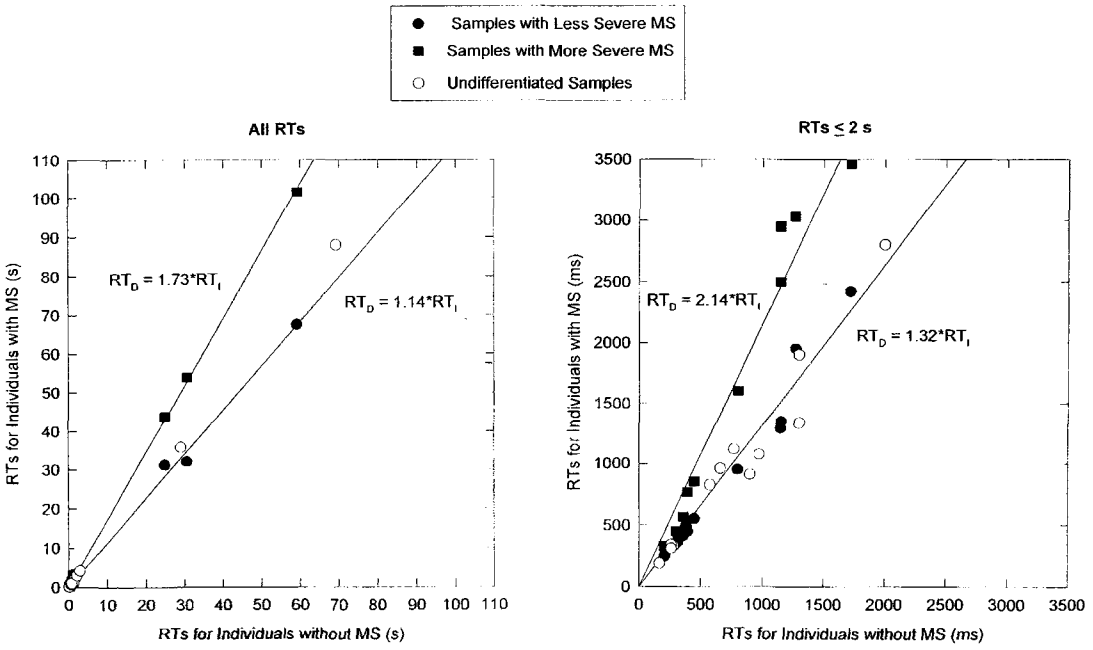

Fig. 2. Each point represents the mean response time (RT) of a sample of adults with multiple sclerosis (MS) from one of the studies listed in Table 2 and the mean RT for the corresponding sample of adults without MS. Squares correspond to RTs for adults with more severe MS symptoms; filled circles represent RTs for adults with less severe symptoms; open circles represent RTs for adults in four other samples from Table 1 that apparently had less severe symptoms. Also shown is the best fitting linear function derived from Equation 6. The left panel depicts all RTs; the right panel shows the RTs in which, for adults without MS, the mean RT ≤ 2s.

their symptoms, and the time since the onset of those symptoms. In addition, many of the samples included individuals who were taking medications that may influence speed of processing. Some but not all investigators excluded individuals afflicted with other CNS disorders, psychiatric disorders, or learning disability. This heterogeneity complicates interpretation of the present results in terms of any single causal factor.

Implications for the Neural Noise Hypothesis

The logic underlying the present work was that MS is a condition in which neurons deteriorate in a manner that can lead to the degraded signal-to-noise ratio that is central to the neural noise hypothesis. Accordingly, if the neural noise hypothesis is correct, RTs for individuals with and without MS should be related in much the same manner as RTs for older and younger adults are related. This predicted relation was obtained: Across different tasks and conditions, RTs for individuals with MS increased as a function of RTs for individuals without MS, just as RTs for older adults typically increase as a function of RTs for younger adults.

Further evidence for the applicability of the MS data to aging comes from the absolute values of m that were obtained for adults with more and less severe MS symptoms. For adults with more severe symptoms, m = 1.73 (for all RTs) and 2.14 (including only RTs ≤ 2s), values that approximate those found for 70-year-olds (Cerella & Hale, 1994). In contrast, for adults with less severe symptoms, m = 1.14 (all RTs) and 1.32 (RTs ≤ 2s), values similar to those for 55-year-olds (Cerella & Hale, 1994). Thus, as predicted, individuals with more severe MS symptoms and (presumably) more neural noise

processed information more slowly than individuals with less severe symptoms and (presumably) less neural noise.

Of course, as was the case with previous efforts to test the neural noise hypothesis, the present findings provide only indirect support for the hypothesis. Because of the many limiting conditions described previously and the fact that the precise nature and magnitude of neural loss was not known for most of the individuals in the samples listed in Table 1, the present findings are best described as consistent with the neural noise hypothesis rather than providing strong tests of that hypothesis. Nevertheless, additional studies of processing speed in individuals with MS would seem to be useful to test some of the implications of the neural noise hypothesis.

Implications for Understanding the Cognitive Consequences of MS

Slower speed of processing is but one of the many cognitive deficits that are associated with MS. As described previously, adults with MS often experience reduced ability to remember and to reason abstractly. In this situation, in which a disorder is associated with a number of different outcomes, a persistent problem is determining whether the disorder is related directly to each cognitive outcome or whether the disorder is directly related to one outcome but indirectly to the others (Salthouse, 1996). That is, individuals with MS often process information more slowly, they remember less accurately, and they are less skilled at reasoning abstractly. Perhaps each of these symptoms is an independent consequence of MS. An alternative, however, is that only one of these processes is a direct consequence of MS and that decline in this process results in declines in other cognitive processes. For example, MS might produce slower processing speed, which then results in reduced memory and reasoning ability.

Researchers studying MS have made little progress on this problem but they may find some useful clues from research on aging. Like adults with MS, older adults process information more slowly and they often are less skilled on reasoning and memory tasks. In this case, aging is associated with slower speed of processing, which affects abstract reasoning directly and indirectly by decreasing the capacity of working memory, which is essential for most reasoning tasks (Salthouse, 1993). Research of this sort could provide the starting point for analyses of the direct and indirect cognitive consequences of MS.

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(an asterisk denotes a study listed in Table 1)

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