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On the Dynamics Between Growth and Decline in the Aging of Intelligence and Memory

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The view of aging and old age predominantly held in Western societies is one of general decline in capacity and efficiency. Older persons are judged to be less efficient, less adaptive, and less intelligent than younger adults. In addition to scientific evidence such as that collected in opinion surveys (e.g., [22]), the view of aging as decline is also evident in cultural products of art [28], as well as in everyday communications in the mass media. The image of old age as a period of decline seems deeply embedded in the social fabric of society.

Counterexamples to this view of aging as decline are considered exceptions to the rule. Individuals undoubtedly exist who perform extraordinary mental and physical feats in old age. Aside from well-known artists such as Pablo Casals, or the pianists Vladimir Horowitz and Arthur Rubinstein, consider the 75-year-old who has run the 42-km marathon in about 3 h 15 min, a time not easily reached by most young adults. Exceptions from aging as universal and inevitable decline, although they do not alter our general view, are important to note because they serve to challenge the boundaries of the "normal" and suggest the value of re-examining the limits of reality. Indeed, the search for the limits and plasticity of aging is the essence of our own research approach. In the area of intelligence, for instance, we are interested in understanding the conditions and range of reserve capacity or plasticity that older individuals hold in intelligence and cognitive functioning.

The view of aging as decline, or decline view, also characterized the beginning of psychological research on aging. During the last decade or so, however, the situation has changed. One much-debated question in the psychology of aging has become whether psychological aging is indeed solely a phenomenon of gradual, cumulative, and inevitable decline. Here, this debate will be illustrated in one research area – the study of intelligence and memory.

What is the scientific evidence on the aging of intelligence and memory? Recent decades have witnessed a number of new findings that challenge the stereotype of general and universal decline [5, 7, 9, 29, 31, 47]. Four lines of research are particularly relevant:

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1. On the nature of aging of each of the several abilities that constitute the provinces of intelligence
2. On interindividual variability and cultural change in intellectual aging
3. On the plasticity (reserve capacity) of intellectual functioning in old age
4. On maximum limits of intellectual functioning

Together, these lines of research have opened a new window on the aging of intelligence and related cognitive functions.

Different Intellectual Abilities Age Differently

Most research on intelligence in adulthood and old age has employed standardized psychometric tests of intelligence. Such intelligence tests are based on a multiability structural conception of intelligence. Intelligence is not seen as a single ability; rather, it is conceived of as a system of multiple abilities. To view intelligence as a system of clusters of mental abilities permits the possibility that different abilities can age differently, in the same manner as different organs of the human body show different rates of aging [14, 20, 43].

In fact, the possibility that distinct intellectual abilities age differently is part of a major psychometric theory of intelligence developed by Cattell and Horn [12, 26, 27]. The central feature of the Cattell-Horn theory of intelligence relevant to considerations of aging is the distinction between two large clusters of intellectual abilities, fluid intelligence and crystallized intelligence. Fluid intelligence deals with the "content-free" basic processes of information processing and reasoning; another shorthand description of it would be that it represents the basic architecture or the basic "mechanics" of intellectual functioning. In order to minimize the role played by cultural content, fluid intelligence is assessed by efficiency of problem-solving with material that is novel or overlearned. Crystallized intelligence, on the other hand, refers to a cluster of subabilities that deal with content- and knowledge-based elaboration of reasoning. Crystallized intelligence, or the "pragmatics" of intelligence, is typically measured by tasks involving language, interpersonal communication, social intelligence, and cultural knowledge. Professional expertise and wisdom are exemplars of crystallized intelligence [16, 17].

What about the life-span developmental fate of fluid and crystallized intelligence, the mechanics and the pragmatics of intelligence? The theory postulates that fluid and crystallized intelligence show rather different trajectories of aging (Fig. 1). The initial course up to early adulthood is identical: both ability clusters show an upward trend. Beginning in middle adulthood, their aging differs markedly. Fluid intelligence is expected to exhibit a fairly early and regular aging loss. Crystallized intelligence, by contrast, is expected to continue growth during adulthood and show stability into old age.

It is now argued that age functions can best be identified when tested at "limits" of performance or reserve capacity: performing tasks under conditions of stress, of a high degree difficulty, or demanding extensive practice (expertise) (Fig. 2). In psychology, testing-the-limits – similar but not identical to stress testing in medicine – may become the chosen method of identifying aging changes both in the basic sci-

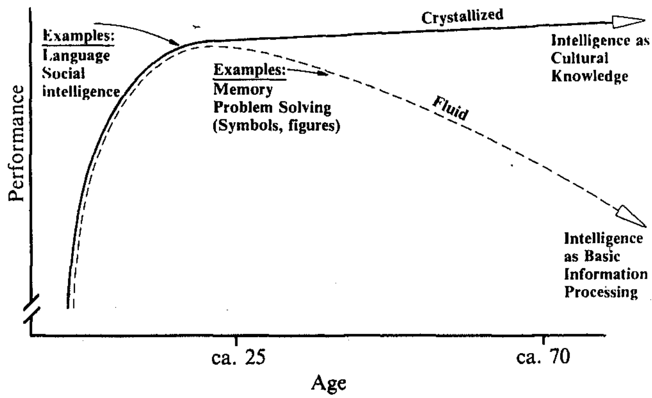

Fig. 1. Postulated developmental trajectories of fluid and crystallized intelligence. (After [12, 26])

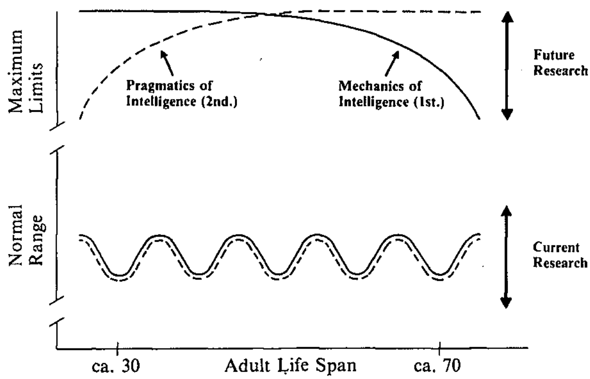

Fig. 2. Testing-the-limits and the aging of the mechanics vs. the pragmatics of intelligence. Age changes affect functioning within the normal range less than at the limits. (After [7])

ence laboratory and in clinical practice [2, 7, 29, 46]. This topic is discussed in more detail later in this paper.

Why should fluid and crystallized intelligence differ so dramatically in their life-span developmental course? According to the theory, fluid intelligence reflects primarily the biological integrity of neurophysiological functioning and brain status. Because these foundations of fluid intelligence are susceptible to biological aging and neurological trauma over the course of life, fluid intelligence is predicted to decline with age, beginning in early adulthood. Crystallized intelligence, by contrast, is largely the manifestation of accumulated experience and cultural learning. As experience and learning continue throughout the life span, crystallized intelligence is expected to show an increase into late adulthood.

The Cattell-Horn theory, then, with its differing courses of aging for fluid and crystallized intelligence, is one of the first examples of the idea that intellectual aging is not synonymous with a general loss of functioning. Different ability clusters of intelligence do indeed age differently; there is both growth and decline during adulthood and old age. Empirical research supports the theory [27, 36]. Whereas most individuals show losses in measurements of fluid intelligence beginning around age 30–40, many individuals equally maintain their level of functioning in crystallized-type measurements, such as on a test of language knowledge, up to age 70.

Cultural Change and Interindividual Variability in Aging

The next line of research involves the study of cultural change and interindividual variability. This research has produced two other findings which demonstrate that the aging of intelligence does not follow a fixed course of continual and universal decline. The findings are a substantial degree of variation in the aging of intelligence (a) between persons and (b) between generations or birth cohorts.

The finding of cultural or historical variation in intelligence was possible because of the development of new research designs better suited to capture age development in a changing society. Whereas traditional research used simple age-comparative designs such as the cross-sectional or longitudinal method, since the late 1960s new methods have been developed that incorporate historical variations into these designs [4, 32, 39]. In part, this development of more complex aging designs occurred because simple cross-sectional and longitudinal studies did not produce the same outcomes. For decades, cross-sectional results had confirmed the expected pattern of loss of intellectual performance with age, beginning in early adulthood around age 30. The emerging longitudinal follow-up data did not show the same decline pattern: instead, in longitudinal studies, individuals up to age 60 or so exhibited little change in intellectual functioning.

One of the major reasons for discrepancy between cross-sectional and longitudinal studies is the existence of historical, cultural change. For these reasons the desired methodology is one in which age and generational or so-called birth cohort membership can be varied simultaneously. This is achieved by the application of so-called sequential strategies which consist of successions of cross-sectional and/or longitudinal studies as shown in Fig. 3.

Using such sequential strategies, Schaie and his colleagues began in 1956 what is now perhaps the classic study on adult and old-age development of intelligence; a study that has revolutionized our conceptions of the aging of intelligence. The study began with 500 subjects and has been continuously expanded at 7-year intervals, involving, as of 1984, a 28-year follow-up of more than 2000 subjects measured repeatedly on a large battery of intelligence tests [40, 41]. Control groups measured at longer intervals are also included (Fig. 4).

Two findings of Schaie's research program are highlighted here: the results on (a) interindividual variability and (b) historical change.

Interindividual Variability. A first major finding in Schaie's research is that of sizeable variability in the overall course of intellectual aging between individuals. Consider, for example, the onset of aging loss as illustrated in Fig. 5. Depending upon

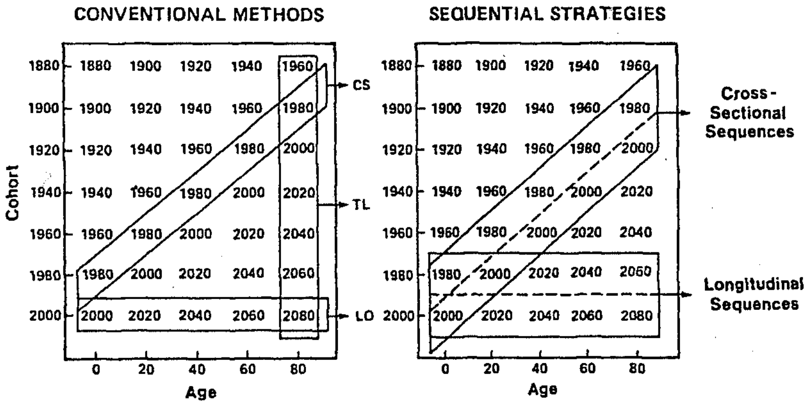

Fig. 3. Cohort-sequential strategies. (After [4, 39])

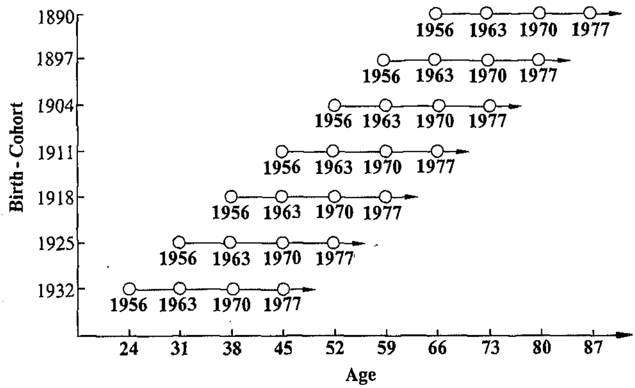

Fig. 4. Sequential strategy of Schaie's study of adult and old-age intelligence [41]

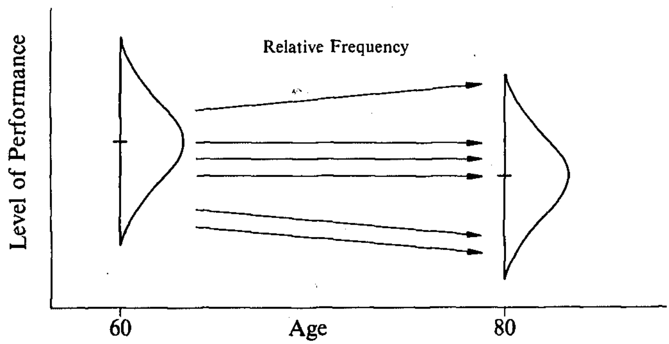

Fig. 5. Substantial individual differences in the course of intellectual aging from age 60 to 80. (After [5])

conditions of health, work context, and similar factors, aging decline can begin for different persons during the fourth, fifth, sixth, seventh, or even eighth decade of life. In current cohorts of fairly healthy American adults, aging loss in intelligence tests does not start before about age 55 for most individuals. However, the data still suggest that if individuals live long enough, aging decline in intellectual functioning is likely to begin at some point, however late [25, 42].

Another statistic offers further information on the relatively low average aging decline. Schaie [41] has shown that average aging decline in his subjects from age 60 to 80 is only about two-thirds of a standard deviation. This implies that about one-third of 70-year-olds perform above the mean of young adults in intelligence tests. In other words, there is a sizeable number of elderly persons who function at high levels even when compared with the yound adult.

Historical Change. The data of Schaie's work [41] also show that performance on intelligence tests does not only change with age, but also with history. Cohort or historical differences between age levels can be as large as longitudinal aging changes within the same cohort. Consider, for example, the findings for one age group, say 53-year-olds, measured at different historical moments (1956, 1963, 1970, 1977, etc.) on five major intelligence abilities. For these 53-year-olds, the five different mental abilities show different patterns of historical change as shown in Fig. 6. Three show positive historical change, one is cohort-invariant, the fifth evinces negative change with historical time.

Because mental abilities change differently over historical time, such cohort effects support further the notion that intellectual aging is not solely a phenomenon of decline. Cohort effects of the magnitude reported in research on adult intelligence are novel to psychologists and perhaps also to neurologists. In our view, aside from the possibility of historical changes in the genome of the population, three clusters of environmental influences are primarily involved as origins of cohort effects and associated variability in the aging of intelligence: cultural changes in education, health, and work. Successive generations, for example, exhibit on the average more formal education and other forms of education-related experiences, such as those

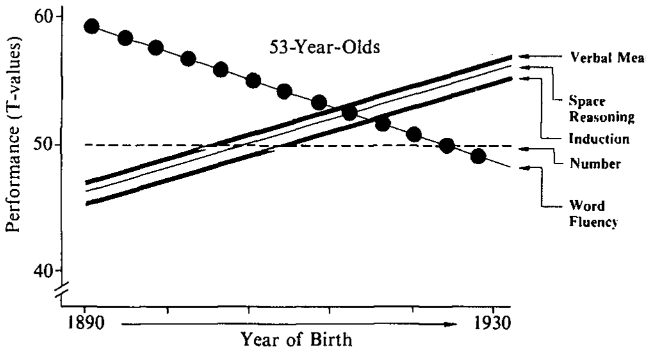

Fig. 6. Historical change: simplified trends representing the average performance of 53-year-olds from different birth cohorts, as estimated by Schaie [41], based on time-lag comparisons

associated with the introduction of television. Many other facets of everyday life show sociocultural change that may be related to level and rate of intellectual functioning. At present, however, it is not yet possible to specify which of the factors are responsible for the cohort changes observed in intellectual aging.

Cognitive Intervention Research on Plasticity in Old Age

The results presented thus far describe what, in one Western cultural context and at a few historical moments, the aging of psychometrically measured intelligence looks like. The central finding is great variability and openness in level and course, between abilities as well as between individuals and historical cohorts. The aging of intelligence is not a rigidly fixed phenomenon that can be captured by simple age designs. No single cohort-specific or ability-specific study tells the final story on the aging of intelligence [4, 35, 38, 39].

Does variability between individuals have a counterpart in plasticity within one individual? The inquiry into variability of intellectual performance within the same person, i.e., plasticity or reserve capacity, has been the direction of our own recent research [10, 29]. We ask whether the variability in level of intellectual performance obtained in descriptive cohort and age comparisons can be simulated as plasticity in single individuals.

Psychological Evidence

One of our central resulting research questions is the following: Is it possible to elevate the level of intellectual performance of elderly individuals by an amount comparable to the one reported either as aging loss or as the difference between same-age persons from different cohorts? To resolve this issue we provide older individuals with added learning experience and practice in intellectual functioning.

Training of Intelligence Test Performance. Meanwhile, some ten cognitive training studies with a total of about 1000 older persons have been completed in our laboratories, in the United States at the Pennsylvania State University (with Sherry L. Willis) and at the Max Planck Institute for Human Development and Education in Berlin (with Freya Dittmann-Kohli). Each of the studies extended over a period of about 1 year [8, 10, 47]. Study participants are between 60 and 80 years of age and above average in health and education. We estimate that our participants, both country and city dwellers, represent perhaps 50%–75% of the 60- to 80-year-olds living in rural Pennsylvania and in Berlin.

In most studies, the training program consists of five to ten training sessions distributed over 1–2 months. Cognitive training focuses on that cluster of intelligence that according to theory and data is sensitive to aging loss, i.e., fluid intelligence. During training, reasoning problems similar to those contained in tests of fluid intelligence are explained, solutions are practiced, and corrective feedback is given.

The results of these various practice and learning studies are highly consistent. As is illustrated in Fig. 7 taken from Baltes et al. [8], older individuals benefit markedly from exposure to cognitive activity. In tests similar to the training focus, per-

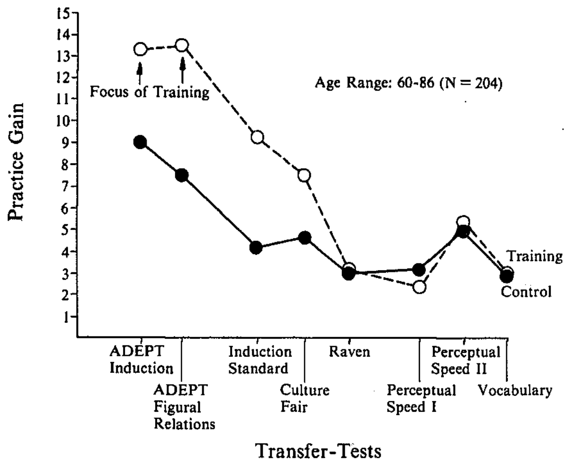

Fig. 7. Results from a cognitive training study conducted in Berlin [8]. The content focus of training was the two major subabilities (figural relations, induction) that constitute fluid intelligence. Training effects were measured by a battery of intelligence tests which differed increasingly (*l* to *r*) from focus of training in the requisite factual and procedural cognitive skills

formance gain is about one standard deviation: an amount rather similar to the aging loss reported in descriptive longitudinal research on this age range [41]. In addition, the training gain is maintained at all occasions studied following the practice sessions, i.e., up to 6 months following the intervention. The evidence for transfer from the abilities trained to other clusters of intelligence, however, is moderate. As might be expected, transfer to training is restricted of tests of intelligence tapping the same ability as that trained.

More refined analyses of test performances also show that trained older adults not only increase their average level of test performance, but are also more accurate (i.e., show fewer errors) and are able to solve more difficult problems than before the training program. Another important finding is that the large majority of participants in our research seem to profit from practice and training. Participants are classified into subgroups by, e.g., subjective health status, age, level of education, initial level of test performance or IQ, but these subgroups do not differ substantially in amount of training gain.

Training of Memory. During the last year we have extended our research on intellectual plasticity and reserve capacity to the area of memory [30]. Our training focus is on memory tasks (such as the well-known digit span) that require subjects to repeat strings of digits or words. Without training, typical subjects are able to repeat four to eight digits or a similar number of words in the correct order (3-1-5-0-8, etc., house-car-family-telephone, etc.).

Using theories of cognitive psychology and memory [13, 18], we have developed training modules that permit subjects to achieve record-like performances. These training programs extend over 30–50 individual sessions. Thus far, we have worked with 15 healthy elderly people in the age range 67–78. In terms of IQ, these subjects are above average. However, they were not selected because they are particularly gifted in memory functioning. In the course of the training programs we engineer an expert memory system that involves the acquisition and combination of three components: working memory, a declarative knowledge system about digits, and a mnemonic strategy (Method of Loci) of encoding and retrieving [30].

As with our research on training psychometric intelligence, in this research on reserve capacity of memory our elderly subjects also prove capable of demonstrating remarkable gains in performance. After 30 sessions of memory training, all elderly subjects can repeat – under self-paced conditions of about 20-s presentation intervals between words – at least 30 words in the correct order after one presentation of the list of words (Fig. 8). As to digit strings, all elderly persons studied so far are able to repeat – again under self-paced presentation rates of about 20-s intervals – strings of digits as long as 40 after they have been presented only once. Our best elderly person can repeat a string of 120 digits with a presentation rate of 8-s;

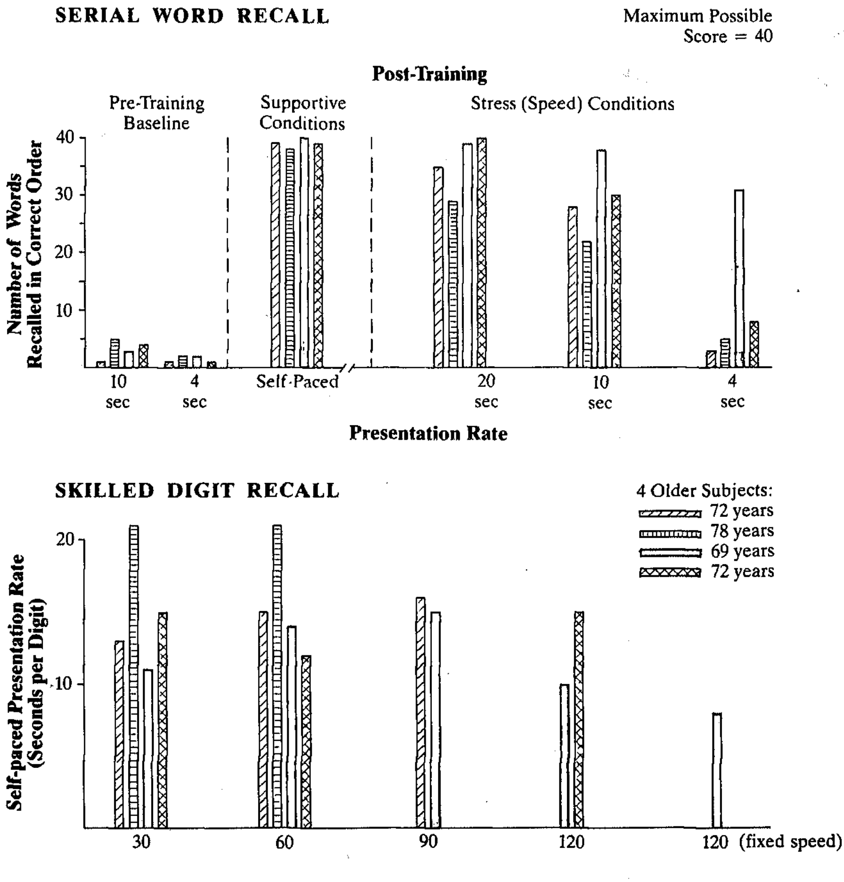

Fig. 8. Research on reserve capacity: performance of four elderly subjects in word span and digit span. (From [45])

on the surface, at least, an amazing performance for a 70-year-old. Note that presenting a string of 120 digits at an 8-s presentation rate takes 16 min.

These memory task performances by elderly people are of such magnitude that they can be classified as approaching the performances of expert mnemonists [18]. Thus the findings suggest that, as in the area of psychometric intelligence, many elderly people have a reserve capacity of memory functioning extending far beyond our everyday and scientific conceptions of what the aging of memory is like.

One missing piece of the puzzle is whether the everyday world of many older persons is indeed one that generates intellectual atrophy, due to lack of experiences and demands conducive to high intellectual performance. Based on casual observation and sociological analyses of role changes following retirement, this seems a reasonable assumption. A major tenet of the sociology of old age is that aging brings with it a loss of social role and involvement, but careful, direct observations of intelligence-related behaviors of older persons are not yet available. An exception, perhaps, is the observational work of Margret M. Baltes from the Free University of Berlin [1, 3]. She has shown that the social ecology of nursing homes is one that steers elderly residents toward dependent rather than independent, self-sufficient behavior. Such research on nursing home residents, however, may not tell the ecological story of fairly healthy older individuals such as the ones participating in the research on intelligence reported here.

To prevent possible misinterpretation of our research on plasticity and reserve capacity, some cautionary comments are necessary. The results do *not* imply the following three conclusions. First, that older adults profit more from intelligence or memory training than young adults. As there are no good age-comparative studies on training gain, no definite knowledge about this question and the extent of reserve capacity or plasticity existing in different age groups is available. Second, that the training programs raised the level of intelligence or memory as a whole to the level shown in younger adulthood. In fact, the gain was demonstrated only for those abilities or components that were part of the training activity.

The third possible misinterpretation would be that all aging individuals display the plasticity reported here. We do not know the subject generality of our findings. While we do believe that most elderly individuals up to age 80 or so are capable of major training benefits as reported here, we need to re-emphasize that our samples are clearly biased towards the healthy elderly and most likely do not include persons who suffer from brain-related diseases such as senile dementia of the Alzheimer type. Certainly there are aging-related disease groups for which we would not expect the magnitude of plasticity demonstrated by our elderly subjects.

Brain-Physiological Evidence

So far we have summarized evidence for plasticity on the level of behavioral assessment of intelligence and memory. Since fall 1984, we have been collaborating with the Max Planck Institute for Neurological Research at Cologne in examining whether the psychological plasticity of intellectual functioning observed in many elderly people has a correlate or counterpart in physiological brain functioning [24]. This collaboration involves the use of positron emission tomography (PET). PET scanning of radiolabelled fluorodeoxyglucose permits the in vivo assessment of cerebral glucose utilization in the brain. It also provides an imaging technique to display the regional distribution of glucose metabolism in various parts of the brain [23, 37].

To date we have studied 20 elderly subjects (ages 68–80): ten participated in 30 sessions of memory training as described above and ten formed a control group. PET scan measures were taken twice, before and after training, approximately 3 months apart. Departing from the usual PET scan procedure, in which scans are performed while subjects are in various resting states, our subjects worked silently on a long memory task for the 40-min measurement period. This strategy allows great control over what subjects do during PET scan.

Three of our research questions are: (a) Does an intensive 30-session memory training produce changes in the metabolic rate of glucose in the brain? (b) If an effect of memory training on brain glucose metabolism is obtained, is it evident only if subjects engage in the specific memory activities trained or is it evident also when other memory activities are performed? (c) If an effect is obtained, is it general to the whole brain or region-specific?

The evidence collected thus far is encouraging. Memory-trained subjects evince a higher level of glucose consumption, about 10% higher than control subjects, in one specific area of the brain (lentiform nucleus: globus pallidus and putamen). Thus the preliminary answer seems to be that continued memory practice can indeed result in a higher level of brain energy metabolism in the elderly – at least in situations when memory functions are called upon. We are currently examining more systematically whether, in addition to the effect in the area of the lentiform nucleus, there are other regional effects in the sense of a continuum of transfer.

We need to be careful not to overestimate and overgeneralize the significance of the findings reported. However, our findings on metabolic brain plasticity fit into another line of research reported over the last few years by others. Evidence is building up that development and growth of the normally aging brain extends into old age [19, 33]. Once, many thought that the brain was fixed in structure and connectivity by the time of early adulthood. Diamond and her colleagues [15] at Berkeley, however, have shown that there seems to be new dendritic growth in the cortex of elderly rats if stimulated through environmental enrichment. Research by Lynch [34], in a similar vein, suggests that growth and deterioration of brain structures exist conjointly throughout the life course. However, according to Lynch the overall proportions of growth and deterioration of brain structures, as measured for instance in dendritic growth following injury, changes across the life span. In old age, growth continues but is reduced in relative magnitude.

Our assumption from a distance is that clinical neurologists may have been more aware of the possibility of further growth in brain structure in old age than psychologists, biochemists or physiologists. What else could lie behind the kind of recovery and compensatory responses often found in elderly patients after sudden brain damage? However, clearer and more direct laboratory demonstration of such growth processes in old age may represent a new level of insight and knowledge about the matter.

In any case, having the special opportunity of speaking as psychologists to a world congress of neurology, we would like to highlight the value and possible excitement of interdisciplinary work. We consider this joint program between two Max

Planck Institutes a rare opportunity. It was possible rapidly to interconnect two recent developments that hold much promise in two otherwise fairly separate disciplinary areas, the bioneurological and the behavioral sciences. Specifically, we were able to combine PET scan methodology, on the one hand, with cognitive-science type psychology on the other.

Age Differences and Testing-the-Limits

Let us return to the psychology of the aging of intelligence and comment further on another research strategy called testing-the-limits. Increasingly, psychologists join in the argument that more sensitive measures of development and aging are available if one tests people at limits of performance [2, 7, 21, 29, 46].

As to aging, for instance, the one definitional criterion scientists agree upon is that aging brings with it increased vulnerability and reduction in system adaptivity [14, 43]. These can both be most easily estimated at limits of performance. Moreover, it is expected that differences between comparison groups, such as age groups, are magnified at the limits.

In our own research on the aging of intelligence and memory, we use testing-the-limits primarily for three purposes. First, it permits study of the extent of reserve capacity or plasticity. Second, it allows at the same time for identification of constraints on plasticity including constraints on intellectual advances in old age. Third, it permits the systematic study of compensatory processes if limits are reached [7, 29, 30].

Consider the two-ability theory of intelligence mentioned earlier. If one takes wisdom as an exemplar of the crystallized "pragmatics" of intelligence [44] and memory for digits as a typical task of the fluid "mechanics" of intelligence, age differences in tasks for these two are expected to be fairly small at baseline, i.e., there is much overlap in the age distributions within the normal or nontrained range of performance. As one moves subjects toward maximum limits or peaks of performance, as can be accomplished through the application of training procedures, the expectation is that the overlap in the age distributions can be reduced. The idealized expectation is that in the end, nonoverlapping age distributions would result, in the present example with opposite directionality for wisdom vs memory for digits (Fig. 9).

For the case of memory for words and digits (a fluid intelligence task), we have conducted such testing-the-limits work on age differences. The outcome, as shown in Fig. 10, is supportive of our expectation. At baseline, subjects of different ages and ability levels differ very little from each other. At limits or peaks of performance, however, arrived at by training subjects and then increasing level of difficulty (speeding up presentation rate), subject differences – including age differences – are magnified. At limits of performance we expect also to be in a better position to study the problem that intrigues us most: the dynamics of growth and decline. How do subjects behave when and if they reach a threshold of performance? In this context, the first author and his colleagues have identified a process called "selective optimization with compensation" as an adaptive strategy prototypical of successful aging [5, 6, 7, 17].

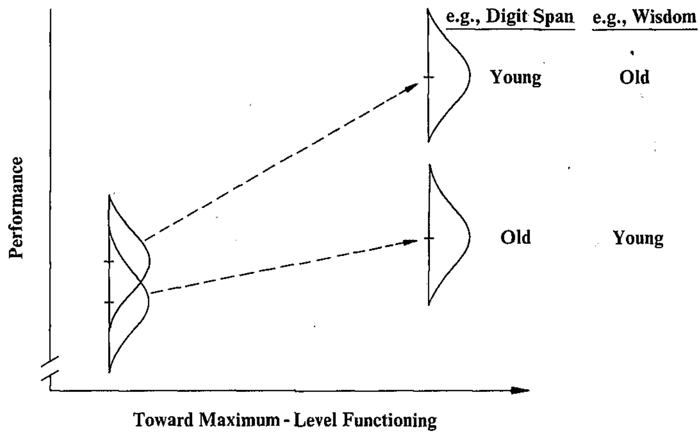

Fig. 9. Unravelling overlap in age-performance distribution by means of testing-the-limits: wisdom vs. digit span

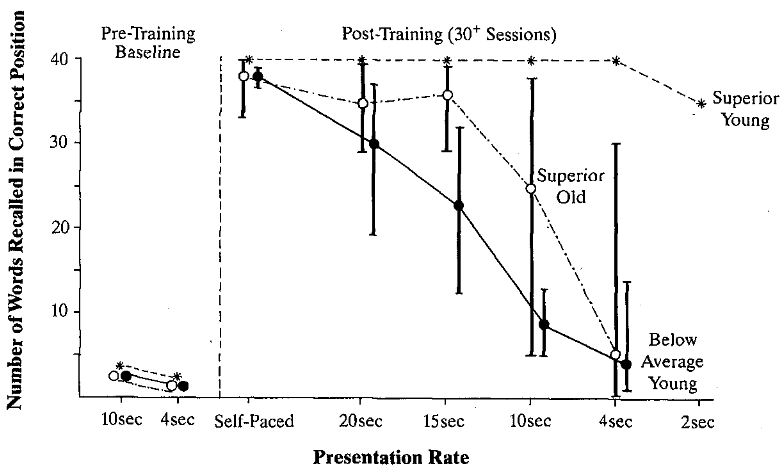

Fig. 10. Age differences are magnified at limits: sample case of skilled memory for words, for three groups. (From [30])

There is much similarity, of course, between our approach of testing-the-limits and methods of stress and adaptivity testing in biology and medicine [2, 14, 20]. However, it seems on the surface that there are also differences in emphasis. Testing-the-limits as we use it is not restricted to one-time static assessments or small variations in treatment. Rather, based on a theoretical analysis of the mechanisms at hand (e.g., memory), we engineer extensive intervention programs, identify progress in select components toward maximum limits of performance, and also test whether, after it has been acquired, the system deconstructs if components are removed [29].

Research on testing-the-limits has broad ramifications. Its possible usefulness extends to many quarters and we assume that similar assessment strategies exist in neurology especially for the purpose of differential diagnosis; consider, for instance, the early diagnosis of senile dementia or the assessment of reserve potential following brain injury. It is likely that systematic use of testing-the-limits procedures – rather than static, one-time measurement – will result in a magnification of group differences and a more sensitive measure of early onset of brain-related diseases. Testing-the-limits lowers the threshold at which a dysfunction can be identified [2]. Moreover, systematic testing of the reserve capacity available to subjects or patients will permit diagnosis of the conditions and range of available plasticity to a given individual. As to senile dementia of the Alzheimer type, for example, there is relevant work in progress at the Department of Gerontopsychiatry at the Free University of Berlin. Margret Baltes, Kanowski, and Kühl and colleagues are examining whether testing-the-limits approaches result in early and more effective diagnosis of Alzheimer-type diseases.

In the long run, the development of such testing-the-limits procedures will be most powerful if theoreticians and practitioners cooperate closely. In psychology, in any case, this is one of the examples where advances in theory and practice seem to make such cooperation imperative: theory-guided analysis of the model of behavior on the one hand, with practice-based application on the other.

Conclusions

The core theme of this article is the search for the real limits, as opposed to the imagined ones, of the aging of intelligence and memory. Contrary to the simple and widely-held view of universal and cumulative decline, the evidence associated with the four lines of research reviewed turned out to be more complex.

Growth and decline in intelligence exist conjointly. Certainly there is decline in old age, especially at maximum limits of functioning in the basic mechanics of intelligence. However, for most normal elderly people there is also great reserve capacity and potential for new learning and growth in those aspects of intellectual functioning that are practiced and selected for further development and specialization. If provided with cognitive enrichment and practice, most elderly people up to age 75 or so are capable of remarkable gains and peaks of intellectual performance, including in those areas of functioning, such as memory, where the typical expectation is one of early and regular decline. Not unlike the Roman god Janus, with his two faces looking in opposite directions and thus at different aspects of life, intellectual aging represents a dynamic between growth and decline. As we move toward old age, this dynamic between growth and decline is likely to increase and become the central drama of life.

This new window on the aging of intelligence was opened by the invention of a new set of methodologies. We have singled out two. First, the advent of cohort-sequential strategies which expanded simple cross-sectional and longitudinal methods to include variation of historical time or cohort. Second, the systematic use of theory-guided intervention and testing-the-limits procedures.

Testing-the limits in particular makes the dynamic between growth and decline most conspicuous. It has not only generated new evidence on remarkable reserve capacity or plasticity of the elderly, but in its search for peaks or maximum limits on performance it has also emphasized the other side of the coin, i.e., the boundary conditions of plasticity. At limits, both positive and negative aspects of aging may be enlarged or accentuated. Moreover, it is in limits of performance that we may have a new research tool available for early diagnosis of aging-related pathologies as well as for the study of compensatory processes following loss of functioning.

It is in the nature of the present evidence that psychological aging is conditioned by the biocultural context in which aging takes place and by what individuals do as they age. It is important, therefore, to bear in mind that the forms of intellectual aging reported here support the conclusion that what we happen to observe in our descriptive research on the natural history of the aging of intelligence is but a sample of what is possible in principle (see also [11]). Existing limits in a given society or in given science are not absolute or necessary ones. In this sense, the search for the range and limits of intellectual plasticity has not only suggested new approaches in the scientific study of psychological aging. It has also opened up new social vistas on what the aging of intelligence could be like if conditions were different.

Summary

In this paper, four lines of research on the aging of intelligence and memory are reviewed: research on (a) differential aging of subabilities, (b) intersubject variability and historical change, (c) plasticity and reserve capacity, and (d) limits of functioning. The nature of intellectual aging is not a simple movement toward loss of functioning. Rather, growth and decline interact in complex ways. Aging loss is most likely to occur at maximum limits of the basic mechanical operations of intelligence. Growth can exist in those aspects (the "pragmatics" of intelligence) in which individuals practice and engage in further evolution of knowledge systems. Testing-the-limits is presented as a methodological strategy by which mechanisms of positive and negative changes of cognitive aging can be identified. Suggestions are also offered for the use of testing-the-limits procedures in biomedical work such as research on senile dementia of the Alzheimer type.

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