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Theory-Guided Analysis of Mechanisms of Development and Aging Through Testing-the-Limits and Research on Expertise

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INTRODUCTION

Two central factors in theoretical explanations of cognitive change in adulthood and old age are the effects of experience and practice. These two factors also predominate in recent models of cognitive functioning in general. A good example is the expertise model in which the acquisition of expertise is described as involving long-term preoccupation with domain-specific knowledge and continuous practice of behavioral routines.

In this chapter, we propose a research framework that combines aspects of the expertise model with a life-span approach. Central to this framework are two assumptions. First, individual differences, and in particular age differences, are best studied if criterion task perfor-

This manuscript is dedicated to Helmut Coper on the occasion of his 60th birthday, in recognition of his biopsychological research on adaptivity across the life span. Research reported in this chapter has been conducted in the context of a project on expertise and aging codirected by Paul B. Baltes and Reinhold Kliegl and carried out in collaboration with Jacqui Smith and Jutta Heckhausen. Discussions with Timothy A. Salthouse, Daniel P. Keating, and Roger A. Dixon helped to clarify a number of theoretical issues. Jacqui Smith, Jutta Heckhausen, Daniel P. Keating, Timothy A. Salthouse, Ross A. Thompson, and the editors of this volume provided helpful comments on an earlier version of this chapter.

mance is assessed close to a person's limits of relevant cognitive functions. Second, it is assumed that controlled (or guided) acquisition of expertise in a laboratory setting and subsequent experimental decomposition of this expertise should yield more precise estimates of individual competence than do traditional one-time or static assessments.

We propose two research strategies that were designed to test these assumptions. Before describing this approach in more detail, we need to point out a limitation of this chapter. The empirical evidence we present is based mainly on case studies. Therefore, no strong conclusions, especially on age-comparative questions, should be drawn at present. The objective of this chapter is to advance a methodological argument rather than to report definitive data.

THEORETICAL BACKGROUND

Expertise and Reserve Capacity

Research on expert performance has emphasized the prominent role of amount and quality of permanent knowledge in cognitive processing (cf. Brown, 1982; Chi, Glaser, & Rees, 1982). However, the study of expertise has two major limitations. First, almost by definition there are few experts in specific domains. Thus the pool of possible research subjects is restricted. Second, because the acquisition of a real-life expertise usually requires many years of practice in the relevant activity, little is known about the natural developmental course of expertise. In fact, only recently has the acquisition of complex cognitive skills become a major topic of cognitive psychological research (e.g., Anderson, 1981, 1982; Chase & Ericsson, 1981).

Both the attractive and problematic sides of the expertise paradigm are illustrated when the paradigm is applied to research on aging. On the one hand, people like Arthur Rubinstein and Picasso are frequently mentioned in the study of superior older experts as exemplars of successful aging: Such people are presented as prototypes of optimized maturity (P. B. Baltes, 1984; P. B. Baltes & Kliegl, 1986). On the other hand, little is known, from a psychological perspective, about how Rubinstein and Picasso accomplished what they did and whether the cognitive processes, or the products, were truly different across their lives. Answers to such questions would add both to the study of expertise and to our understanding of successful aging (P. B. Baltes, Dittmann-Kohli, & Dixon, 1984; P. B. Baltes & Kliegl, 1986; Charness, 1981; Denney, 1984; Hoyer, 1985; Salthouse, 1985).

In principle, successful aging should be possible for the majority of healthy older adults. The achievement of a state of effective functioning involves the actualization of *reserve capacity:* The term is introduced here to communicate the notion that most people can improve, one way or another, on baseline performances. Experts are commonly defined as persons whose performance on some criterion task is far superior to that of normal persons (see, e.g., Chi et al., 1982). Experts are persons who have actualized their reserve capacity in a specific domain of functioning. Actualized reserve capacity in the form of an expertise is different from more transient or temporary types of performance improvement. Therefore, we have distinguished between baseline performance, baseline reserve capacity, and developmental reserve capacity (P. B. Baltes et al., 1984; Kliegl & Baltes, 1984).

Baseline performance denotes an individual's ability or skill inferred from his or her performance in one-time assessment under standardized conditions. Standardized conditions usually include specification of tasks, tests, instructions, and response options. Baseline reserve capacity refers to the range of baseline performance under varying conditions of demand and support. Demand and support conditions include levels of difficulty of task, variations in instruction, motivational conditions, and perhaps short-term practice. Finally, developmental reserve capacity is defined as the level and range of performance under extended periods of development (including aging) or extended periods of practice. This latter concept introduces a time and developmental dimension. We will refer to such developmental reserve capacity as latent potential (P. B. Baltes & Willis, 1982). Among the conditions qualifying under this category would be instruction and long-term acquisition of expertise.

Actualization of developmental reserve capacity should inform about latent potential and limits of functioning in old and young persons. Moreover, laboratory studies of age-related trade-offs in cognitive processes and knowledge may be used to test one important aspect of one model of successful aging called selective optimization with compensation: High levels of cognitive functioning can be preserved by restricting the area of competence and investing more and more time and effort to maintain high levels of efficiency in this narrow domain of functioning (P. B. Baltes & M. M. Baltes, 1980; P. B. Baltes et al., 1984; Dixon & Baltes, in press).

Testing-the-Limits and Research on Expertise

To illustrate the potential gained by integrating theoretical principles of the expertise paradigm and models of aging, two complementary research strategies will now be proposed. Both strategies can be seen as belonging to a methodology called testing-the-limits or learning-tests (M. M. Baltes & Kindermann, 1985; P.B. Baltes & Kliegl, 1986; Guthke, 1982; Kliegl & Baltes, 1984; Schmidt, 1971; Wiedl, 1984). The strategies proposed in this chapter differ mainly in their emphasis on theoretical specification and experimental control over criterion task performance.

The first strategy, *theory-guided synthesis* or *engineering of cognitive expertise,* is devised to identify limits in performance as subjects progress through a structured, componential training program that leads to expert performance. Concretely, we demonstrate how young and older adults with normal memory span for digits and nouns prior to training can, after training, approach the performance levels of professional mnemonists. The second strategy, *adaptivity* or *resilience testing of expert systems,* involves exposing subjects who have reached levels of expert performance to increasingly more difficult conditions until a situation is reached in which the functional reserve of the expert system is overtaxed.

One assumption underlying the combination of expertise and aging research is that iterative application of the two strategies may reveal latent potential and limits of cognitive functions more clearly than traditional aging research. A second assumption is that, if subjects perform according to the components specified by the particular theory that guided the development of the training program, it is possible to pinpoint more precisely the nature of the components involved in age-related differences.

How can actualization of developmental reserve in memory span contribute to an understanding of successful aging in general? We would like to offer three answers. First, if the question of the nature of successful aging is to be approached experimentally, we need laboratory analogs. Such analogs are easier to generate if they are based on well-defined tasks. Whether a memory expertise in digit and word span tasks is representative of more common expertises in the arts and in sports, in our opinion, is largely a matter of historical and cultural preferences.

Second, although memory span tasks may not initially appear to be very representative of the complex processes associated with successful aging, we will show that very high demands on creativity and originality lie at the roots of the memory expertise engineered in our laboratory. Actually, the displayed memory performance could be considered an epiphenomenon of creative thought. Thus, acquisition of expertise in the present paradigm changes the task from a simple to a complex and probably representative one.

Third, in principle, actualization of developmental reserve can be elicited in other cognitive processes provided that (a) there is available an explicit model of the expertise that is to be engineered so that a theory-guided training program can be devised, and (b) subjects have available adequate normal physical and motivational resources. For example, there are attempts to define wisdom as an expertise in matters of life review and life planning and to construct tasks in these domains that focus on cognitive processes such as search for relevant information and heuristics of decision (Smith, Dixon, & Baltes, in press).

Cognitive Processes and Knowledge

The interplay of cognitive processes and accumulated life experiences in the form of specialized knowledge has become the focus of attention in recent models of adult cognitive and intellectual development (P.B. Baltes et al., 1984; P.B. Baltes & Kliegl, 1986; Charness, 1981; Denney, 1984; Hoyer, 1985; Labouvie-Vief, 1982, 1985; Salthouse, 1985). A similar distinction has guided cognitive theories about differences between experts and novices (Brown, 1982; Chi et al., 1982).

In P. B. Baltes et al.'s (1984) dual-process, life-span model of intellectual functioning, the distinction between cognitive processes ("mechanics of intelligence") and various aspects of knowledge ("pragmatics of intelligence") is central because—as with Cattell's (1971) and Horn's (1982) theory of fluid and crystallized intelligence—different developmental trajectories are expected for the two components. If measured at very high levels of performance (i.e., close to maximum performance or at the level of experts), "mechanical" efficiency of cognitive processes is assumed to decline, whereas quantity and quality of select aspects of "pragmatic" knowledge might be expected to remain stable or evince even further growth with age. Growth, however, is assumed to be restricted to those select domains of knowledge that are regularly used and practiced. Primary evidence for this proposition is the differential developmental change in fluid and crystallized abilities (Cattell, 1971; Horn, 1982; Schaie & Hertzog, 1983) and Denney's (1982, 1984) work buttressing her model of intellectual aging that distinguishes between optimally exercised and unexercised abilities.

The distinction between fundamental cognitive processes and knowledge upon which these processes act has also proven to be very useful in theories about expert-novice differences. There is a consensus and some evidence (e.g., Chase & Simon, 1973; Sloboda, 1978) that experts and novices generally do not differ in fundamental cognitive processes, that is, the basic mechanics of intelligence. Rather, amount, organization, and transformation of knowledge appear to be the hallmarks of expertise (Chi et al., 1982). Consequently, there has been a shift from the emphasis on describing fundamental processes toward a focus on understanding the structure and representation of knowledge. A similar redirection in research and theoretical focus may be needed to further our understanding of developmental and individual differences in cognitive functioning in adulthood. However, to realize this objective, ways must be found to control knowledge involved in criterion tasks: Without such control, inferences about differences in cognitive processes might not be valid (Estes, 1982; Glaser, 1984; Weinert & Hasselhorn, 1986).

Age Comparisons of Peak Performance

Becoming an expert in a real-life domain is a developmental process that takes time, much practice, and preoccupation with the topic. With respect to these factors, old age may hold advantages as time lived offers a longer period of experience. In addition, however, various skills may have as a prerequisite for expert performance a certain amount or level of capacity in their component processes. Also, for some performances, components may be required and thresholds may be involved that represent necessary antecedent conditions.

It is conceivable that there may be individual (and perhaps some age-related) differences in the amount of capacity required for the development of an expertise. Thus, becoming an expert in old age may be even more difficult if certain cognitive processes such as speed of information search decline. This point can be illustrated with an example from sports: Would it be possible for an 80-year-old to jump higher than 2 m, assuming age-related decline only in basic physical resources such as muscle strength, with everything else, such as knowledge of technique and motivational level, being equal? Whereas with appropriate formal training and knowledge such a height clearly is within reach of young persons, most would agree that it should be close to impossible for an older adult.

Staying with this example for a moment, assume young and old persons are asked to jump across a bar at a height of 1 m on the basis of expert formal training and knowledge. Clearly, aging effects would be reduced because basic physical resources need not be activated to the same degree. Notice that the complexity of the task has not changed because, in principle, the same "algorithm" can be used to jump over each height. Mastering a greater height implies primarily that the task is more difficult. Thus, in the example, magnification of age differences does not arise for reasons of task structure or complexity but because of differences in task difficulty, with the more difficult one requiring more of the available reserve capacity of relevant physical processes. It follows that—holding practice and related experience constant—it may be possible to assess an individual's range of capacity in basic components by varying task difficulty independent of variation in task structure.

Advantages of Constructed Versus Naturally Acquired Expertise

There is another important point that can be communicated with reference to the high-jump example. If an expert wanted to display his or her best performance on a well-known problem, he or she would execute a highly routinized sequence of actions. Any departure from normal strategy or any switch to a different strategy would almost inevitably lead to a substantial drop in performance, perhaps only temporarily, however. For example, if a high jumper gets out of step, often the jump is not even executed. Similarly, although instruction and practice of different styles (e.g., straddle or Fosbury flop) may lead to similar achievements, a person who has trained exclusively in one of them cannot switch to another without experiencing at least a temporary drop of performance.[1]

Relatively little is known about the components or the integration of processes in real-life expert performance involving cognition. Usually experts in cognitive skills were "found in the field" and their expertise was decomposed a posteriori with the help of creative experiments (e.g., Chase & Simon, 1973). In contrast to this procedure and to the sports analogy, the present approach aims at synthesizing or constructing expertise in a laboratory setting with relevant declarative and procedural knowledge specified a priori and, consequently, under experimental control. This is a distinct and critical advantage not available in research involving real-life experts. Knowing how an expertise was acquired and how an expert-level performance is accomplished paves the way for a detailed determination of boundary conditions in criterion task performance at the level of theoretical components putatively underlying aggregated performance. Thus, rather than having to infer differences due to expertise from expert-novice performance differences in a criterion task, the constructed expertise research paradigm allows a priori prediction about expert-novice differences because the components determining performance are known. Moreover, individual differences can be assessed directly at the level of these components at various stages in the acquistion of the expertise.

Hypotheses Related to Aging and Expertise: Toward Magnification and Identification of Age Differences and Aging-Sensitive Components

In the following discussion, five sets of guiding assumptions and hypotheses that motivate our search for an alternative developmental methodology are presented (Kliegl & Baltes, 1984).

[1] There are expertises that are constituted by creative variations of procedures (e.g., chess, tennis). We will limit our discussion to expertises that depend on highly overlearned procedures.

First, we contend that psychometric or experimental data with one or few assessments are comparable to asking nonexperts to jump over a fairly low height such as 1 m. In addition to differences in fundamental processes and knowledge, individual and age differences in clearing such a low height may arise for an infinite number of reasons such as familiarity, motivational level, and past experience. Thus, within this normal range of functioning many alternative interpretations are plausible. The conventional approach to this problem has been to demonstrate the relevance or irrelevance of a small subset of these factors by experimental or correlational techniques. It is an open question, however, whether these strategies can ever be conclusive.

A related problem is the substantial malleability of performance under standardized one-time assessments. Results from cognitive intervention studies showed that the estimated longitudinal decline in fluid abilities can be compensated by a "life experience" of five 1-hr sessions (P. B. Baltes, Dittmann-Kohli, & Kliegl, 1986; P. B. Baltes & Willis, 1982; Willis, 1985). A comparable degree of plasticity is found in other domains of functioning of the elderly as well, such as behaviors associated with social interactions and self-care (M. M. Baltes & Kindermann, 1985; Lerner, 1984). In our view, this finding of substantial malleability is in large part due to the fact that the performances measured were not near the top but in the average range of performances. Thus, independent of how much young subjects would benefit from similar training, standard psychometric assessment does not lead to the identification of robust age differences. Data of this type are also moot with respect to reserve capacity or potential to improve. Although data from psychometric assessment were perhaps never meant to speak to notions of reserve capacity, demonstration of test-performance modifiability in short-term intervention implies that theories of aging need to incorporate notions of reserve capacity. Ignoring these results implies the rather strong assumption that amount of change due to intervention is constant across age.

Second, like Salthouse (1985; Salthouse & Somberg, 1982) we posit that measures of reserve capacity can be obtained in studies with extended practice that lead subjects to very high levels of performance. Ideally, an expertise should be constructed in a laboratory setting. The criterion of attained expertise would be a level of performance on a criterion task that may be many standard deviations better than the performance of untrained subjects. Since acquisition of a cognitive skill with extended practice seems to follow a power function, the asymptotic level could be used as an index of maximum performance (Anderson, 1982; Newell & Rosenbloom, 1981). The distinct advantage of measuring reserve capacity under conditions of extended practice and in the context of constructed expertise is that high levels of performance guarantee task execution according to theory. The experimenter knows that certain cognitive processes and specific knowledge were activated since any other strategy would fall short of such high performance levels.

Third, in analogy to the high-jump example, we postulate that larger and larger age differences in basic cognitive processes should be found with increasing task difficulty (P. B. Baltes et al., 1984; Craik, in press; Craik & Byrd, 1982; Craik & Rabinowitz, 1985; Salthouse, in press). Since construction of laboratory expertise involves the theoretical specification of a number of cognitive processes, differential sensitivity to aging-related loss should become visible. Although decline is expected on some, many cognitive processes may remain stable even under, or sometimes because of, conditions of high demand. Stability is also predicted for acquisition of new declarative knowledge.

Fourth, once an expertise is established at a stable level, we argue that it is possible to test the functional reserve, adaptivity, or resilience of the system by selectively interfering with component processes and/or knowledge critical for correct performance on the criterion task. If these kinds of interference are possible in a quantitative, continuous manner, boundary conditions of gradual recovery versus deterioration of the expertise can be identified. Again, age effects are expected to be pronounced on such measures of resilience or adaptivity. In a review of age effects of adaptivity in thermoregulation, motility, and animal learning, Coper, Jänicke, and Schulze (1986) concluded that "a progressive reduction in adaptation to environmental conditions . . . is the most important phenomenon associated with aging" (p. 208; see also Fries & Crapo, 1981; Shock, 1977).

Fifth, we postulate that the ability to cope with challenging situations such as "loss" of a specific cognitive component process may also open the way for experimental investigations of compensatory processes. Both psychologically (Bäckman, 1984; P. B. Baltes et al., 1984; Salthouse, chapter 8 of this volume; Skinner, 1983) and physiologically (Phelps & Mazziota, 1985), the evolution of compensatory processes has been featured in accounts of effective aging. Performance recovery under more difficult or more complex conditions implies a change in kind or in efficiency of cognitive processes or in the relevant knowledge. Often these changes may involve creative transformations of the expertise leading to its reestablishment at a higher level.

Obviously, in cases of self-initiated compensatory or substitutive behaviors, subjects take their expertises beyond what they were taught in the training program and beyond the strict experimental control afforded by theory-guided synthesis. It is likely, however, that this process of restructuring is confined by the extant expertise. Especially with selective componential interference, the locus of compensatory processes is probably easily determined. Nevertheless, post hoc decompositional analysis and verbal protocols, just as in traditional research on expertise, will be required. The positive aspect, however, is that construction of expertise in a laboratory setting is expected to trigger adaptive processes of knowledge transformation and refinement which are characteristic of real-life experts.

In the next two sections, preliminary results from several case studies will be used to illustrate the interfacing of the two complementary research strategies described: theory-guided synthesis of expertise and subsequent testing of the adaptivity of this expertise. The joint application of these strategies should lead to empirical tests of the theoretical positions advanced in this section. The substantive focus is on engineered digit memory in young and old adults. More detailed information is contained in several research reports (Kliegl, Smith, & Baltes, 1986; Kliegl, Smith, Heckhausen, & Baltes, 1986a, 1986b; Smith, Kliegl, & Baltes, 1986).

THEORY-GUIDED SYNTHESIS OF MEMORY EXPERTISE

Theoretical Framework

Theory-guided synthesis of expertise involves systematic instruction and practice; one may even describe it as "shaping" the desired expertise. There are two unique aspects of this research strategy: One, a normal subject must achieve a stable level of expert performance in the course of a laboratory program. Two, the combination of cognitive processes and relevant knowledge involved in expert task performance is substantially different from those that untrained subjects bring to the task. With both conditions fulfilled, the display of expertise guarantees that the cognitive processes and domains of knowledge that constitute the theoretical components of expert performance on a criterion task were actually involved during task execution.

In digit span tasks, subjects are typically required to report in correct order a series of random digits that was presented to them once. On the average and with presentation rates of several seconds, untrained subjects can recall about seven items if they rehearse the individual digits during presentation. If, however, by chance a sequence of digits can be recoded into a meaningful element of permanent knowledge, for example one's phone number, the number of digits recalled could be substantially larger because limits associated with a rehearsal strategy apply to the number of chunks (Miller, 1956). Indeed, some form of recoding of random digits into meaningful knowledge has been the hallmark of most mnemonists (Ericsson, 1985). Similarly, two subjects who in the course of 2 years learned to recall more than 80 digits relied heavily, for example, on knowledge related to athletic running times to recode short digit sequences (Chase & Ericsson, 1981).[2] Thus, one difference between normal, untrained subjects and memory experts is that memory experts have available systematic digit-related knowledge.

Once digits are recoded into meaningful knowledge elements, more effective strategies than simple rehearsal can be employed to retain information about the order of items. A particularly useful strategy is known as the Method of Loci (cf. Bower, 1970; Yates, 1966). In the Method of Loci an overlearned sequence of geographic locations is used repeatedly (trial-invariant) as a memory peg for encoding a trial-dependent sequence of knowledge elements. Subjects are instructed to generate funny, bizarre, and dynamic images or thoughts between the to-be-remembered items and the sequentially ordered geographic locations. During recall, the geographic locations serve as retrieval cues for items and their serial position. Again, most professional mnemonists use this or similar mnemonic devices (see Bellezza, 1981, for a review). Thus, a second difference between normal, untrained subjects and memory experts is that memory experts have available special techniques that allow them to retain order information of random series of items.

Procedure

We engineered memory expertise in normal subjects using the two factors mentioned: knowledge about digits and the Method of Loci as a mnemonic strategy of encoding and retrieval. Digit-related knowledge was provided by having subjects learn a large number of historical dates. When the subjects were presented with a long series of random digits, this knowledge was used to recode consecutive digit triplets into historical dates by prefixing a 1 (e.g., 4–9–2 becomes 1492, and is associated with "Columbus discovers America"). This way, parsing a random digit sequence into digit triplets and recoding these triplets into historical events results in a random sequence of historical events. Encoding and retrieval of a random sequence of historical events should be possible with the Method of Loci.

Subjects were systematically trained in the memory expertise. First, they overlearned a specific trip around either 30 or 40 Berlin landmarks. Second, they practiced the recall of concrete nouns with this mental

[2] Chase and Ericsson (1981) identified three critical components of this expertise. In addition to recoding digits in elements of permanent knowledge, their subjects organized these recoded units in a trial-dependent hierarchial retrieval structure and improved on the speed with which they could carry out associated cognitive processes.

map. In a third step in our training program, subjects learned dates for 100 historical events. Finally, they attempted to integrate these components to recall strings of digits.

Subjects

So far, 1 young student (age 23 years) and 10 older adults (age range 67–78 years) have participated in 30 training sessions.[3] None of the subjects had prior experience in mnemonic strategies, and all had normal digit and word spans. Their general intelligence (Hamburg-Wechsler IQ) was 1.5 to 2 *SD* above the mean for their respective age groups. The elderly subjects were recruited from the top 20% of a positively selected sample of about 400 persons who had participated earlier in a cognitive training study on fluid-type intelligence tasks (Baltes et al., 1985). Thus, the selection strategy maximized chances of identifying mentally very fit elderly. No such special selection criteria were applied to our young subject, a personal acquaintance of members of the research team.

Results

Performance of a young adult subject. After memorizing a map of 30 Berlin landmarks and 100 historical dates, our young subject immediately mastered the Method of Loci using concrete nouns. He also had no difficulty in employing the Method of Loci and knowledge of 100 historical events to memorize long digit lists. These were composed of random concatenation of triplets selected with replacement from the pool of 100 historical events that represented the subject's knowledge.

During the first trials our young adult correctly recalled 90 digits presented at an average self-paced rate of 12 s per digit. After 36 trials he recalled 90 digits presented at a fixed rate of 5 s per digit. Thus, after only 36 trials (and after 20 experimental sessions), with low time constraints and with suitable mnemonic techniques, the subject performed at expert level with very little instruction. Further progress of this subject will be described in a later section on adaptivity testing.

Performance of older subjects. The 10 older subjects memorized a map with 40 Berlin landmarks. Using this map as part of the Method of Loci mnemonic, all subjects could recall more than 32 of 40 nouns,

[3] Another young and 2 old persons were instructed according to a different model involving recoding of digits into concrete nouns instead of historical dates (Kliegl et al., 1986). Results are in agreement with the ones presented here.

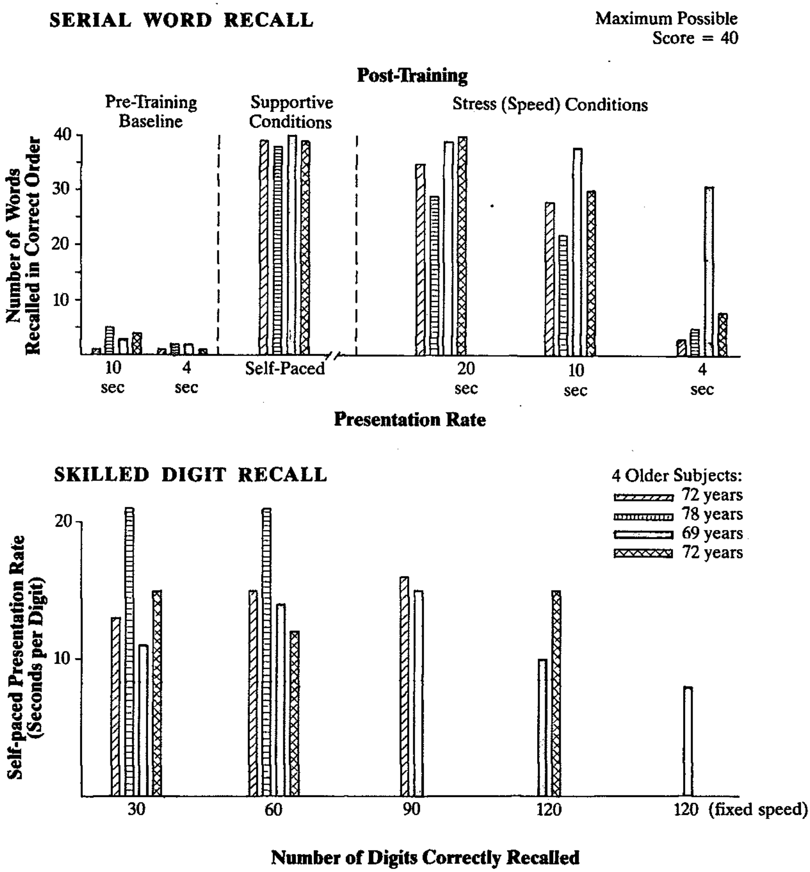

Figure 1. Magnification of individual differences in serial word recall (under speeded conditions) and digit memory (self-paced) for four subjects.

provided the study time for each word was self-determined (i.e., self-paced presentation format).

There were, however, large individual differences in the number of sessions subjects required to reach this level of performance. Only 4 of 10 elderly subjects completed all components of the training program within 30 sessions. Their post-training performances on serial recall of 40 nouns are displayed in the top part of Figure 1. These subjects showed close to perfect recall in the self-paced condition.

Like the young adult, once these older subjects had mastered the mnemonic strategy and learned the historical dates, they had little difficulty applying the model to recall long lists of digits. The performances we have observed so far are displayed in the bottom panel of

Figure 1. All 4 elderly subjects recalled correctly strings of 30 and 60 digits, respectively. Two of them succeeded also with strings of 90 and 120 digits. In all these trials, subjects determined the successive presentation of digits. The best performance we have observed was by a 69-year-old woman who correctly recalled 120 digits presented in a fixed interval of 8 s. Note that it takes 16 min to present such a long string. Preliminary as they are, these data suggest substantial developmental reserve capacity of memory processes in mentally fit old persons.

Age comparisons. Age comparisons on the basis of the present data with few subjects can, of course, illustrate only our general hypotheses. It is fair to admit that we were surprised by the ease with which our best old subject achieved her level of performance. We expected developmental reserve but not to this extent. Nevertheless, and without any intention to belittle the achievement of the best elderly person of a highly selected sample, her performance does not approach the speed of processing of our 1 young subject. Data from several other, IQ-equivalent young subjects currently in training show a similar superiority. Counter to our expectations, the best elderly subject, however, performed better than young subjects with low to average general intelligence (Kliegl et al., 1986). We predict that young subjects of equivalent intellectual and motivational level will clearly outperform the best older subjects at high levels of performance.

What about the mechanisms possibly involved in the magnification of age differences at limits of performance? None of the 10 older subjects had problems in learning 100 historical dates. Only one subject could not recall reliably the mental map of 40 locations in correct order even at the end of the training program. Our elderly subjects seemed to have difficulty in producing and encoding such images, not in principle but at the speed required for efficient performance under fast presentation rates. This was especially the case for 6 of these subjects: They required about 30 training sessions to apply the Method of Loci successfully to lists of 40 concrete nouns that were presented at subject-paced rates or at fixed rates of 20 s per word.

Individual differences among the other 4 subjects were also apparent for efficiency in the Method of Loci when nouns were presented in faster, fixed intervals (see Figure 1). In addition, these data show a strong correspondence between levels of performance in recall of nouns and recall of digits. Thus, in the present memory expertise, the formation of bizarre, funny, or dynamic images or thoughts required in the use of the Method of Loci appears to be the critical process displaying sensitivity to aging.

Thought or image formation is a rather complex cognitive process which is itself dependent on knowledge and other cognitive processes. Two complementary strategies could be advocated. First, the aging-sensitivity of thought or image formation should be cross-validated in a different criterion task. This would imply constructing an expertise, for example, in a memory-independent problem-solving task. Second, thought formation can be pushed to its limits in an extant expertise such as cognitively engineered digit memory. This might induce the need for compensatory processes and shed new light on the constituents of the cognitive process of interest. This research strategy will be illustrated in the next section.

ADAPTIVITY TESTING OF EXPERT MEMORY

Often it is difficult, if not impossible, to know whether a change in task characteristics affects difficulty or the nature of the cognitive components involved (e.g., the complexity of the system). Depending on the reserve capacity associated with relevant cognitive processes, it may affect either or both. The situation should be different if task performance is at an expert level. In this case, a person can display a high level of performance only if he or she complies with the theoretically specified schedule of task execution (recall the example of a high jumper who will mark a personal record height only if he or she uses the practiced technique).

As long as increases in general constraints do not change the level of performance in an expertise or there are no major drops in performance, it can reasonably be assumed that task difficulty is increased without changes in the components constituting the expertise. For example, one of the elderly subjects' recall of 120 digits was not impaired by switching to a fixed presentation rate (see Figure 1). In this case, we are tapping the functional reserve of an extant system with specified components.

If we observe a significant drop in performance, limits of current functional reserve or system adaptivity are reached. In our example of increased speed of stimulus (i.e., digit) input, the drop signals either that there was not enough time to execute the required mental operations or that alternative, perhaps random or compensatory operations were invoked. Thus, a sustained drop in performance indicates that the task cannot be performed using the current level of expertise. Subsequent practice might lead to greater resilience or functional reserve due to a more efficient execution of component processes in an unchanged expert system.

The situation becomes more complicated—not unlike the typical situation in the study of real-life expertise—if environmental pressure forces a refinement of the expertise either in basic cognitive processes (e.g., combining two operations into one) or in the relevant knowledge (e.g., narrowing the spread of activated knowledge elements or elimination of irrelevant features). In this instance, separation of changes in the cognitive system from increases in efficacy of the same system may not be easily possible. Additional experiments would be needed to determine the cause of increased resilience. Nevertheless, we would anticipate that the advantage of working with well-specified laboratory expert systems continues to exist as further experimentation can be conducted against the backdrop of a well-known system of functioning.

Increasing task difficulty without changing the system is not the only way to study an expert system at its limits. Mapping functional reserve can also involve testing of single components of the system, for example, by selective interference. Two kinds of information can be gained from selectively interfering with certain components. First, any interference with a theoretically postulated component must lead to a drop in performance. If it does not, there was an error in the model specification, or automatic refinement of the expertise made this component obsolete. Selective interference serves as a validity check on the theoretical specification. The second advantage of selective interference is the possibility of experimentally inducing the need for compensatory processes and, if they materialize, their subsequent identification. Obviously, causes for improvement on a criterion task can be identified more directly if one knows where in the expertise the need for compensation existed.

The example given so far distinguished between variation in task difficulty and in the components of the system. Thus, in the following, we distinguish between testing-the-limits by variation in constraints on the criterion task and testing-the-limits by selective interference with theoretical components of the system. Note that we are primarily interested in observing and understanding two phenomena: first, why subjects cannot perform certain tasks (lack of adaptivity); and second, the adaptive processes that lead to a gradual restoration of performance after the expertise has been overtaxed by these strategies. Examples for both procedures are illustrated with data from one high-ability young subject (Kliegl et al., 1985).

Increasing Task Difficulty Within an Extant System

The first column of Table 1 specifies the parameters of a baseline expertise in digit memory at the end of a theory-guided synthesis of cognitive skill. The subject recalled correctly all 90 digits presented at a rate of 5 s per digit. Digit strings were composed by random concatenation of digit triplets based on a pool of 100 historical dates.

Table 1. Resilience Testing of an Expertise in Digit Memory

	Baseline of expertise	Intervention			
		1	2	3	4
Criterion Task					
Percentage of digits recalled in correct order[a]	100	50	50	48	80
Parameters of Expertise					
Length of digit string					
Compatibility with historical knowledge (%)	100				
Number of loci	30				
Order of loci	known				
Content of loci	known				
Pool size of triplets	100		25	25	100
Presentation rate (s/digit)	5	3	2	1	3
External cues at encoding	no				
External cues at recall	no				
Additional load on working memory	no				
Number of trials to restore expertise	n.a.	n.a.[b]	13	26	4

Note n.a. = not available
[a]Percentages reflect drop in first trial of intervention.
[b]Expertise was not restored after sixth trial.

There was perfect compatibility between the digit strings and the subject's historical knowledge. The expertise involved 30 loci with known order and content. Finally, the subject did not use any external cues.

The first intervention involved an increase in presentation rate to 3 s per digit. Performance dropped to 50% and was not restored during six trials in this condition. The subject reported that it took too long to decide which features of a historical event should be used for thought or image formation. Following up on this report by the subject, the next step in our training program involved identifying unique features for a subset of 25 events and having the subject memorize these. For example, instead of invoking the historical event "Crusade" to form his image, he would always use a simple "cross" when the digits corresponding to the Crusade event had to be recoded.

As a second intervention, digit strings based on random concatenation of triplets and consistent with these transformed historical events were presented at a rate of 2 s per digit. Again, performance dropped to 50%. After 13 trials, however, he could correctly recall 90 digits at this 2-s pace. The next step was to increase presentation rate to 1 s per digit. Performance was restored perfectly after 26 trials. Subsequently, we returned to the conditions of the first intervention (i.e., 100 historical dates, 3 s per digit). Performance dropped to only 80% and was restored after four trials.

This short iteration of intervention and practice illustrates how performance improved because of adaptive refinement or even transformation of knowledge. Thus, even simple manipulations of presentation rate can cause a change in expertise-relevant knowledge. It is not clear from these data to what degree there was a concomitant improvement in the efficiency of cognitive processes. Without information about the changes in relevant knowledge, an incorrect, sole attribution to increased efficiency in basic cognitive processes such as retrieval speed would have been likely.

Increasing presentation rate is but one example of increased task demands. Presenting more than 90 digits would be another. Table 1 displays a number of parameters of the expertise that could be manipulated to challenge the expertise. Since the memory expertise was constructed according to a certain model, destabilization can be induced at rather specific levels.

Selective Componential Interference

Construction of expertise implies knowledge of processes that are relevant for task execution. Following theory-guided acquisition of expertise, subjects can be prevented from using some components by experimental manipulation. In our research on digit span based on knowledge of historical dates and the Method of Loci, interference can disable, for example, the use of historical knowledge or the use of the mental walk in the Method of Loci (see also Chase & Ericsson, 1981, for similar, though a posteriori, strategies aimed at testing the cognitive processes used by their subjects).

Interference with use of historical knowledge was achieved in the present case by presenting digit strings that could not be parsed into the historical dates available in the subject's permanent knowledge. When presented with completely random sequences of digits (rather than digits compatible with the subject's knowledge of historical dates), the subject's performance fell immediately within the range of nonexperts (i.e., to about 9 digits) even with relatively slow presentation rates of 10 s per digit. Thus, historical knowledge was critical for the task. Note that the resilience or functional reserve of the expertise could be determined more precisely by manipulating the degree of compatibility between historical knowledge and digit strings.

In the present type of expertise, another example of selective componential interference can focus on the procedural component (i.e., the Method of Loci) involved in long-term memory and retrieval. Application of the Method of Loci requires knowledge of a set of landmarks and of a walk covering them in a fixed order. Our expert can easily encode 30 concrete nouns and their serial position using this technique. Interference with order of locations was achieved by prompting the subject each time a noun was presented on the screen with one of the Berlin landmarks in a new (random) order and requiring him to form an image involving noun and the prompted landmark. In addition, the subject was asked to remember the serial position of nouns. Our prediction with respect to this interference with established order of locations was the following: Forming images between nouns and landmark prompts in unfamiliar order should lead to a complete recall of the set of nouns. Recalling them in correct order, however, should be severely impaired, unless compensatory strategies are employed.

As predicted, the subject correctly recalled 38 of 40 words and the first 18 words also in correct position. Although there was clear interference with order information, performance was still remarkably high, suggesting that the subject had attempted some compensatory measures.

Toward the Study of Compensatory Processes

We have mentioned already the significance of compensatory and substitutive processes for the study of intellectual aging (Bäckman, in press; P. B. Baltes & M. M. Baltes, 1980; P. B. Baltes et al., 1984; Dixon & Baltes, in press).[4] The present pilot work illustrates how testing-the-limits of an extant expert system can be used to gain information about how subjects generate compensations.

In the interference study just described, the subject was able to recall 18 words in the correct position, although our experimental effort was aimed at eliminating serial information. As noted in his verbal report, the subject had accomplished this by attempting to incorporate the serial number of the noun into the image. Thus, the image formed for the first noun and first locus prompt would involve a "1," the image for the second noun and second locus prompt a "2," and so on. This compensatory strategy worked for the first 18 nouns.

A second subject, also experienced with the Method of Loci, generated spontaneously a different compensation. She formed stories between nouns and prompted locations. To retain order information, she designed stories that involved a taxi driving from the prompted landmark to the location normally encoding the order information. The subject correctly recalled 34 words and 25 of them in the correct order. Again, there was a drop in performance but also successful compensation.

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[4] This is true not only for psychological conceptions. For example, biologists (Waddington, 1975) and sociologists (Featherman, 1983) have argued that effective life-span development involves channeling of competence and specialization. The expertise paradigm is a direct realization of notions about channeling and specialization.

Although these examples have only anecdotal qualities, they illustrate the interaction of specific knowledge and cognitive processes. In both cases, new elements of knowledge were incorporated in the task: numbers in the first and a taxi ride in the second example. As a consequence, image or thought formation had to synthesize three instead of two elements during each cycle.

In summary, we believe that even the few data on testing of functional reserve and adaptivity of expert systems generated important facts. Since experts strive for good performance, they are ready to demonstrate high efficacy. As long as possible, they stay within the confines of the systems and increase time-related efficacy. It appears that if within-system functioning is not sufficient, they respond with great creativity to environmental challenges of their expertise. Successful restoration may not only maintain the skill but also reestablish the expertise at a quantitatively and qualitatively higher level. This is accomplished by refinement or enlargement of specific knowledge or by increasing the efficiency of cognitive processes. Both solutions qualify as compensatory strategies which lead to an elaboration of the earlier expertise. In our view, they characterize adequately what we are likely to observe in real-life functioning.

We have not systematically collected data on old persons with respect to questions involving elaboration by compensation. Our expectation is that adaptivity testing of this kind may be especially suited to study compensatory and adaptive processes across the life span. Of particular interest is the question whether refinement of knowledge is more dependent on already available knowledge (the pragmatics of intelligence), possibly favoring older persons; or more indicative of cognitive or learning abilities (the mechanics of intelligence), which would be in line with the strengths of younger persons. At the outset, different developmental trajectories for cognitive processes and knowledge were postulated. In resilience testing of expertise, an understanding of relations and mutual dependencies between these components assumes an important role.

CONCLUSIONS

There is increasing interest in understanding the mechanisms at the basis of growth and decline in cognitive development during adulthood and old age (P. B. Baltes et al., 1984; P. B. Baltes & Kliegl, 1986; Denney, 1984; Dixon & Baltes, in press; Labouvie-Vief, 1982, 1985). It has been argued that growth and decline can be better understood if studied at limits of performance and under controlled laboratory conditions simulating real-life settings of expertise acquisition and development.

Theory-guided synthesis and subsequent systematic destabilization of complex cognitive skills were introduced as complementary testing-the-limits research strategies for assessment of developmental reserve capacity and mechanisms of functioning. Actualization of reserve capacity qualifies a person as an expert if his or her performance on a criterion task is significantly (e.g., several standard deviations) above the mean of a normal, untrained sample of comparable intellectual ability. With this criterion, theory-guided synthesis of expertise secures an advantage of experimental control over active cognitive processes on every trial of a criterion task. We presented results from case studies documenting the feasibility of this approach with young and old subjects.

Developmental reserve capacity can also be measured by indices of adaptive resilience or functional reserve. We have presented three strategies to this end: increasing task demands within the extant system, measuring the time it takes to restore the previous level of criterion task performance, and identifying the type of compensation that subjects use when the extant system is tested beyond its limits of functioning. Thus, the paradigm also offers a view at adaptive and compensatory strategies. Hypotheses about different developmental trajectories for cognitive processes and domain-specific knowledge could be assessed with such measures. Age effects may be most prominent on cognitive processes that govern the adaptive refinement of task-specific knowledge systems.

Some words of caution are in order. Once testing *beyond* the limits of an extant system has started, the further development of expertise may be to a larger degree under the subject's control than is desirable from the experimenter's point of view. Yet, aside from the argument that this departure from an extant system simulates comparable phenomena in real life, we believe that assessment of elaboration and compensation is still aided by departure from a known system. Moreover, so far our experience was that expert subjects are quite eager, interested, and possibly skilled in communicating their compensatory strategies. Of course, resources will prevent large sample studies of iterative resilience testing, but much can be learned from few subjects and efforts at obtaining verbal protocols (Ericsson & Simon, 1984). Furthermore, what was learned can subsequently be incorporated in the engineering part of newly designed research.

Presenting the general strategy of expertise construction, selective componential interference, and elaboration by triggering compensatory strategies was also placed in the context of age comparison. Available data are restricted to limit testing of an extant system by increasing task demands. Magnification of age and individual differences at limits of functioning were obtained. It was speculated that similar magnification may be obtainable if the focus is on elaboration and compensation. If the interest is in aspects of adaptivity, performing experiments at limits of performance may actually be the only way.

We would like to reiterate that, in our view, the combination of theory-guided synthesis of expertise and its subsequent enhancement by systematic destabilization and fostering of compensatory strategies captures some of the dynamics of real-life situations. In this sense, we believe that our efforts aimed at simulation of expert systems in the laboratory may evince higher ecological validity than tasks of digit span initially seem to suggest. In our view, laboratory research on potential and limits in acquisition of expertise and on resilience of expertise in challenging and sometimes overtaxing situations will contribute to knowledge about changes in everyday cognitive functioning in development and aging.

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