Learning

Rule Extraction and Representation

Editors

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6. Imposing Structure on an Unstructured Environment: Ontogenetic Changes in the Ability to Form Rules of Behavior Under Conditions of Low Environmental Predictability

Peter A. Frensch, Ulman Lindenberger and Jutta Kray

6.1 Introduction

Learning is typically defined in terms of an organism's ability to modify its own internal Knowledge Structure in order to accommodate internal and/or external demands (e. g., 1). Often, the modification of internal Knowledge Structure is directed toward increasing the consistency with the structure of the external environment, and indeed, most existing research on human and animal learning is concerned with how organisms come to internally represent systematic structural features of the environment (cf. 1; 2); contributions to this volume). By manipulating the features of the environmental structure, research looking into the link between environment and learning has generated a considerable deal of knowledge about the properties of learning mechanisms that are operative both in humans and in animals under different learning conditions.

However, humans at least are also capable of dealing with unpredictable, unstructured environments in highly systematic ways; that is, they are capable of modifying their internal Knowledge Structure, i. e., of learning, even in the absence of environmental systematicity. Put differently, humans are able to form stable rules of behavior even when these rules of behavior are not anchored in the structure of the external environment.

The main focus in the present chapter is on the human ability to learn, that is, to form internal rules of behavior, under conditions of low environmental structure. Clearly, learning under these kinds of conditions must be strongly influenced by the properties of the organism's information-processing system within which learning takes place. Consequently, individual differences in the formation of internal rules of behavior must reflect, to a large extent, individual differences in the human information-processing system.

Our focus is on potential ontogenetic changes in the human ability to generate internal rules of behavior under conditions of low environmental structure. In the first phase of the research program described in this chapter, we want to demonstrate that there indeed exist age-related differences in the ability to learn, that is, to form internal rules of behavior, when the environment is unpredictable. In a second phase of our research, we attempt to trace age differences in learning under conditions of low environmental structure to age differences in the functioning of the information-processing system.

The chapter is divided into two conceptually distinct parts. In the first part (i. e., sections 6.2–6.5), we examine, both theoretically and empirically, potential age-related changes in the ability to generate internal rules of behavior under conditions of low environmental structure. In the second part (i. e., section 6.5), we consider whether this ability may be related to age differences in the functioning of the human information-processing system. Specifically, we empirically assess the relation between rule-formation ability and a general marker of cognitive functioning, namely performance on fluid intelligence tests (3–7).

Sections 6.2 and 6.3 are devoted to a discussion of the existing literature in an attempt to determine whether there is theoretical reason to believe that the ability to form rules of behavior when the environment is unpredictable changes with age. Because a key requirement for the ability to generate internal rules of behavior when these rules are not represented in the environment is the ability to have control over one's own information processing – an ability we term 'cognitive control' henceforth – we first discuss the psychological reality of the cognitive control concept, and show, on the basis of both psychological and neuropsychological evidence, that the control of one's processing is functionally separable of the processes that are controlled. In the second section, we summarize existing research in the areas of cognitive development and cognitive aging that appears to demonstrate that cognitive control ability may diminish with increasing age. These findings imply, albeit weakly, the possibility of ontogenetic changes in the ability to generate internal rules of behavior under conditions of low environmental structure. In the third section, we introduce a new experimental paradigm that can be used to investigate age differences in the ability to generate internal rules under conditions of low environmental predictability, and describe the results of an initial experiment with this paradigm.

In Section 6.5, we briefly discuss the nature of age-related decline in general information-processing functioning that has been described in the literature, and demonstrate that age-related changes in information-processing functioning, captured by measures of fluid intelligence, are empirically related to the ability to generate rules of behavior when the environment is unpredictive.

6.2 The Concept of Cognitive Control

A key requirement for the ability to learn, i. e., to form rules for the regulation of behavior when the environment is not structured, is that one is able to exert control over one's cognitive processing. In this section, we present a brief overview of the existing literature on the concept of "cognitive control" with the aim of demonstrating that such an ability does indeed exist in humans and is functionally separable from other types of cognitive processing.

The term "cognitive control" is meant to encompass a whole variety of different regulatory processes that are logically required to ensure successful task completion. For the purposes of this chapter, we define "cognitive control" somewhat loosely as cognitive activity that is not directly concerned with the processing of task-relevant information, but is nevertheless necessary to achieve error-free performance on one or multiple tasks that are performed either in isolation or in parallel. The distinction between processes that are concerned with task-relevant information – for which we will use the term elementary processes henceforth – and control, or regulatory, processes that initiate, supervise, stop, and redirect elementary processes, can be likened to the difference between basic procedures and control structures in many computer programming environments. Basic procedures store information in registers, read information out of registers, compare different pieces of information, modify information in some specified way, and so on. In contrast, the control structure regulates when basic procedures are to be performed, which procedures are performed in parallel, which ones serially, which ones need to be cascaded, which ones not, which particular piece of information is processed by which procedure, what to do if procedures fail, and so on.

In cognitive-processing terminology, elementary processes encode environmental information, store and represent information in memory, retrieve information from memory, transform information, and so on. Control processes, or executive control processes, as they are sometimes called (e. g., 8; 9), are responsible primarily for scheduling and initiating elementary processes, for monitoring the processes while they are executed, and for evaluating the results of executed processes. Control processes may not be under conscious control but may operate automatically and without attentional (10; 11).

6.2.1 The Psychological Reality of Cognitive Control

The basic distinction between cognitive control processes and elementary (i. e., to-be-controlled) processes has been part of virtually every general information-processing theory of the cognitive system since the early 1960s (e. g., 12; 13). Atkinson and Shiffrin (12) seem to have introduced the notion of cognitive control into modern information-processing models of cognition by distinguishing between memory structures, on the one hand, and control processes, on the other hand. The distinction between control processes and memory processes, writes Shallice (14), "was introduced by the analogy of the relation between what a human programmer writes at a remote console and the computer hardware and built-in program that the written program controls" (p. 395). Control processes were defined as processes that "are not permanent features of memory, but are transient phenomena under the control of the subject" (12, p. 106).

As a more recent example of the many theories in which the assumption of cognitive control processes figures prominently, consider the model of working memory that was developed by Baddeley and Hitch (15), and has served as a catalyst for much of the recent research on working/short-term memory. Baddeley and Hitch argue that working memory consists of multiple, functionally independent subsystems. Two of the subsystems serve primarily to manipulate speech-based information (phonological loop) and visual information (visuo-spatial sketch pad). These systems are capable of storing information and of performing relatively simple elementary processes on phonological and visual information (e. g., rehearsal). The Central Executive is a controlling attentional system that supervises and coordinates the processing in these two "slave" systems. Given the complexity of the Central Executive and the relative simplicity of the phonological loop and visuo-spatial sketch pad, it is perhaps not surprising that while our understanding of the basic processing in the two slave systems has increased rather sharply over the past twenty years, the same cannot be said for our understanding of the Central Executive. Specifically, it is not known at this time which processes are and are not under the control of the Central Executive nor is it known how control processes change with practice or age.

6.2.1.1 Psychological support

Empirical studies that speak to the functional independence of control and elementary processes come from two main lines of research, experimental studies employing a dual-task methodology, and neuropsychological research. A large number of dual-task studies has addressed the general question of whether one particular cognitive control mechanism, namely the coordination of two tasks that are performed concurrently is functionally independent of the ability to perform the individual tasks, or, put differently, whether there exists a general time-sharing ability. Early research on this question was characterized by, largely factor-analytic, approaches in which the main question of interest was whether subject variance in combined (Tasks A and B) task performance could be predicted by variance on the separate tasks, A and B. If this was the case, such was the reasoning, then a time-sharing ability did not exist. If, on the other hand, unique variance on the combined tasks could be demonstrated, then it could be concluded that time-sharing ability was independent of the ability to perform the tasks in isolation.

Early factor-analytic studies on time-sharing have yielded generally mixed results on the question of whether a time-sharing ability is independent of the ability to perform the tasks in isolation, and have been severely criticized in recent years on methodological grounds. Ackerman, Schneider, and Wickens (16), for example, have argued that unique variance on dual-task performance may reflect unreliable measurement error, rather than time-sharing ability. The few recent studies that have successfully escaped this criticism (e. g., 17–21), have generally been in support of a time-sharing ability. Yee, et al. (21), for instance, asked subjects to simultaneously perform a verbal and a visual task (verbal and auditory in a follow-up experiment) at two times of measurement. At Time 1, both tasks were performed in isolation as well. Yee et al. (21) then used a regression approach to partial variance due to performance on the individual tasks from the variance on the combined tasks obtained at the two times of measurement. The two resulting residual scores were reliably correlated and, in addition, correlated reliably with the residual scores obtained from a second procedure in which a verbal and an auditory task were performed simultaneously. Yee et al.'s (21) findings indicate that the simultaneous execution of two tasks requires an ability that is independent of the ability to perform the individual tasks in isolation. These results provide indirect support for the functional independence of elementary processes and at least one particular control process, coordination.

The simultaneous control of two tasks adds additional burden to the cognitive system even when the two tasks are selected such that interference is minimized (e. g., 22). For example, McLeod (23) gave his participants lengthy practice on a pursuit tracking task in which they were required to keep a spot of light in contact with a target at the same time as they were responding by saying "high" or "low" to a high or low pitch tone. Detailed monitoring of the tracking performance showed no specific effect of the concurrent tone reaction response indicating that interference between the tasks was minimal. Nonetheless, simply knowing that the next trial was one in which a tone response might be required, caused a small amount of general impairment in tracking skill, even when no response was actually made. Following a later and more detailed study, Shallice, McLeod, and Lewis (24) concluded that even when interference is minimized and participants are highly practiced, a decrement of around 10% in performance occurs as a result of the requirement to perform two tasks simultaneously.

Most dual-task studies simply demonstrate that the simultaneous control of two task results in overall performance decrements that are not linearly predicted by performance on the two tasks in isolation. A study by Kelso, Southard, and Goodman (25) goes one step further by showing that the need to control two tasks simultaneously may affect the way in which the component tasks are performed. In this study, participants were required to reach out and touch targets of varying sizes at various distances with their right and left hand. As is well known from Fitts Law (26), the time it takes to strike a target increases as it becomes smaller or is moved further away. However, when participants are asked to touch a small and distant target with the left hand and a large target that is close by with the right hand, then the right hand is slowed down such that the two hands hit the targets at the same time. This "coupling effect" very nicely demonstrates how cognitive control processes may impose themselves on elementary processes.

6.2.1.2 Neuropsychological support

Perhaps the most persuasive evidence in support of the functional difference between control and elementary processes comes from neuropsychological patients suffering from the frontal-lobe syndrome. The frontal lobes of the brain have over the years constituted one of the most fascinating and yet frustrating puzzles in neuropsychology (27). Whereas earlier investigators (28; 29) did not observe significant deficits in patients with frontal-lobe damage, more recently obtained evidence points to the frontal lobe's crucial role in planning, organizing, and controlling cognition and action (e. g., 30). Relative to other brain regions, the size of the frontal lobes reaches a maximum in humans, where they comprise about 40% of the total brain volume (31). As one would expect from a system serving regulatory functions, the frontal lobes have a very rich system of connections with lower levels of the brain and with virtually all other parts of the cortex (32).

Many frontal-lobe patients show deficits on tasks that pose high demands on cognitive control. Two typical examples are the Wisconsin Card Sorting Test (WCST) and tests of verbal fluency. In the WCST, patients are given a pack of cards where each card contains a pattern that is made up of various shapes that vary in color, size, and surround. Patients are instructed to sort the cards into piles on the basis of a rule. Once the patients are able to follow the rule without making errors, the rule is changed. Normal subjects can sort the cards according to different rules relatively easily and quickly, without making many errors. Patients with frontal-lobe damage, however, tend to learn the first rule, and then appear unable to switch to a new rule, demonstrating a high number of errors that tend to be perseverations based on the first rule.

The patients' perseverations are easily explained in terms of a cognitive control deficit (30). That is, patients appear to have lost the capacity to interrupt and change ongoing activity. Once a particular task strategy has been selected and implemented, it continues to run and cannot be modified. Interestingly, many of the frontal-lobe patients who show this pattern, also exhibit a deficit that has been termed "utilization behavior" (33). It appears that for these patients, environmental stimuli often take over the functional role of that part of the cognitive control system that initiates action. For example, when a glass is placed on a table in front of these patients, the patients will grasp it. If a bottle of water is then placed next to the glass, they will seize it, fill the glass, and drink the water, regardless of whether it is appropriate to do so or not (34). Such behavior is rarely observed in normal subjects or patients with damage to different parts of the brain, thus supporting the assumption that the frontal lobes are involved in the cognitive control of action.

Patients with frontal lobe damage also show remarkable deficits on verbal fluency tasks where subjects are asked to produce as many words as possible from a given category such as furniture, or words beginning with a given letter, such as B. Frontal lobe patients are typically able to produce only three to four items per minute, whereas normal subjects produce at least a dozen (35). Patients also frequently make mistakes and produce words that do not belong to the required category or repeat the same words several times.

Again, the patients' difficulties in the verbal fluency tasks can be explained if it is assumed that parts of the frontal lobes are dedicated to cognitive control. The task is difficult presumably because no routine, overlearned program for generating items exist that could be run off without control. Instead, the patients need to set up a retrieval strategy and monitor that the produced items come from the correct category and are not repetitions.

The frontal lobes also seem to play an important role in the ability to inhibit goal-irrelevant information (36). The classical test to assess this ability is the Stroop Color-Word Test (37), where the participant is asked to name the color of the ink in which an incongruent color-name is written (e. g., the word *red* printed in green ink). Performance on the Stroop, and on other tests of inhibition such as the Gottschalt Hidden Figures Test (38), is differentially impaired in patients with frontal lobe damage (39). In line with this observation, recent analyses of event-related brain potentials in monkeys and normal humans strongly suggest that activity in the prefrontal cortex is related to response inhibition (36; 40; 41), and that anterior regions of the cortex with high connectivity to the frontal lobes may be involved in a neural process for error detection and compensation (42).

In summary, there exists both experimental and neuropsychological evidence supporting the functional independence, or separability, of elementary processes and at least some control mechanisms. Furthermore, in theoretical models of the cognitive system, or parts thereof, such as the Baddeley and Hitch's (15) model of working memory, control and elementary processes are typically separated. Together, these findings allow for the possibility that the developmental trajectories of control and elementary processes are different.

6.3 Age Differences in Cognitive Control

In this section, we examine whether current knowledge about the age gradients for some cognitive control processes is at least compatible with the idea that cognitive control ability varies with age. We first present some information on frontal-lobe development because current evidence and theorizing emphasizes that the frontal lobes are implicated in cognitive control processes. We then review the evidence on two types of control processes, separation/coordination and inhibition/monitoring. As argued above, the finding of age differences in cognitive control would be suggestive of ontogenetic changes in the ability to generate internal rules of behavior under conditions of low environmental structure.

6.3.1 Frontal-Lobe Development

Of all regions of the brain, the frontal lobes are the last and most slowly to develop. The area occupied by the frontal lobes increases rapidly during the first two years after birth, then again from about four to seven years of age, and reaches its final size during adolescence. In terms of connectivity, a period of synapse accumulation reaching its peak at two years of age is followed by a period of progressive synapse elimination, or pruning, that is not completed before late adolescence. Moreover, myelination of the frontal cortex occurs relatively late and continues throughout the teenage years (43). With respect to the other end of life, certain areas of the frontal lobes, such as the prefrontal cortex, appear to be among the first to show neuroanatomical and functional signs of aging-induced deterioration (44–47).

6.3.2 Coordination and Separation

Evidence in the fields of both cognitive aging (for a summary, see 48) and child development (49; 50) suggests that the magnitude of age effects increases as a function of task difficulty. In other words, both for children and older adults, differences to younger adults are generally larger with more difficult tasks. As a corollary, age by task-difficulty interactions in response times often disappear when scaled in proportional metric. For example, 10-year-old children and 65-year-old adults may, on average, respond 1.6 times slowed than young adults, which means that absolute differences in latencies are larger under more difficult experimental conditions.

Salthouse (51) and others (52; 50) have argued that this empirical regularity is easily explained in terms of age differences in the average duration of processing steps. We concur in this judgment. However, the regularity effect is equally well explained by the cognitive-control hypothesis if we assume that cognitive control demands, on average, tend to increase with task difficulty. Thus, without further specification, the fact that more difficult tasks produce larger age effects does not discriminate between speed-of-processing hypothesis and cognitive-control accounts.

To allow for differential predictions, one possibility is to distinguish two components of task difficulty: amount of processing (i. e., number of processing steps), and complexity of processing (i. e., cognitive control demand). Two studies in the field of cognitive aging allow for such a distinction (53; 54). Charness and Campbell (53) found that control costs associated with coordinating the components of a complex mental-calculation algorithm increased with age and that age differences in coordination costs were not attenuated by practice. Mayr and Kliegl (54; see also 55) investigated age differences in figural reasoning under task conditions that differed in coordination demands (high versus low). At equal levels of difficulty across task conditions (operationally defined on the basis of young adults' latencies), age differences were more pronounced when coordination demands were high. Thus, the results of both studies suggest that the costs associated with the coordination of information within complex tasks are especially high for older adults.

In contrast, studies using a dual-task paradigm to investigate age differences in coordination/separation ability have provided a more mixed picture. When age differences in single-task performance were eliminated by individualized adjustment of difficulty levels, concurrence costs (i. e., the drop in performance when performing the two tasks together) were sometimes equivalent in young and old adults (56) and sometimes greater in older adults (57–59). When no adjustments were made, proportional adult age differences were of about the same magnitude under single and dual-task conditions (60), which would mean that young and old adults experience concurrence costs of equivalent magnitude. Similar discrepancies in results are found in the child-developmental literature (61; 62).

In our opinion, the apparent invariance in concurrence costs across age found in some of the age-comparative dual-task studies should be interpreted with caution. First, separation (i. e., the ability to keep two tasks as separate as possible) may be easier than coordination in the narrow sense (i. e., the ability to interconnect two concurrently performed tasks), especially if the two tasks involve different modalities. Second, standard dual-task paradigms vary the crucial source of difficulty (i. e., cognitive control demands) at only two levels by comparing single with dual-task performance. Clearly, control difficulty needs to be manipulated across a wider range to obtain more conclusive evidence.

6.3.3 Inhibition and Monitoring

Using the Wisconsin Card Sorting Test (WCST), Chelune and Baer (63) observed that the tendency to commit perseveration errors decreased during middle childhood. Similar results were obtained with tests of field independence, such as the Embedded Figures Test (EFT; 64), where participants perceive conflicting cues and have to overcome the tendency to respond to the more salient cue to make a correct response. Children's performance on the EFT improves until it reaches an asymptote in the middle teenage years (65). Finally, inhibition ability as measured by the Stroop Color-Word Test (37), shows gradual performance increments during childhood and adolescence up to early adulthood (66–68).

These findings are consistent with the claim that cognitive control processes, such as inhibition ability, promote developmental change in fluid intelligence. To obtain stronger evidence, one would need to know more about the relationship between measures of fluid intelligence and inhibition ability. Unfortunately, child developmentalists have rarely looked at such measures in combination. A notable exception is a study by Case and Globerson (69) who found a rather high correlation between the Children's Embedded Figures Test and Raven's Colored Progressive Matrices in a sample of forty-three 7.6 to 8.6 year-old children ($r = .40$; corrected for attenuation, $r = .53$).

In the field of cognitive aging, an increasing body of experimental research points to pronounced age differences in memory updating (70–72), memory for source and context information (70; 73–76), memory for processing errors (77), and inhibition ability (78–81). Moreover, inhibition and monitoring abilities as assessed by standard procedures, such as the Wisconsin Card Sorting Test (82; 83), the Embedded Figures Test (84; 85), and the Stroop Color-Word Test (66; 86; 87, show first signs of decline in the late 50s and relatively pronounced decrements thereafter.

6.3.4 Summary

With respect to cognitive control processes presumably supported by the frontal lobes, the available evidence points to a decrease of coordination and separation abilities in old age, to an increase of inhibition and monitoring abilities during childhood, and to a decrease of these abilities in old age. Together, these findings allow for the possibility that the ability to form internal rules of behavior in the absence of environmental structure, as an ability that requires direct cognitive control, might change with age as well. The available evidence also allows for the possibility that age-related changes in this ability might be related to age-related differences in general cognitive functioning. In the next section, we introduce a new experimental paradigm that can be used to empirically assess age differences in the ability to learn under conditions of low environmental predictability, and describe the results of an initial experiment with this paradigm. In sections 6.5 and 6.6, we are concerned with the relation between age differences in learning under low environmental systematicity and age differences in general cognitive functioning, as assessed by measures of fluid intelligence.

6.4 Age-Related Changes in the Ability to Form Rules of Behavior Under Conditions of Low Environmental Predictability

The main purpose of the experimental task described below was to allow for an assessment of age differences in learning in a situation where the environment changes randomly and thus unpredictably. In this section, we first briefly describe the experimental task. Then, we discuss the main results obtained with a first experiment using this task.

6.4.1 The Continuous Monitoring Task

Figure 6.1 shows the basic setup of the Continuous Monitoring Task (CMT) from the viewpoint of a research participant. When performing the CMT, participants were seated in front of a computer screen. On the screen, two half-circles were displayed, one located spatially above the other. Two features of the upper half-circle, its size and its brightness, were controlled by the computer; the corresponding features of the lower half-circle were controlled by the research participant.

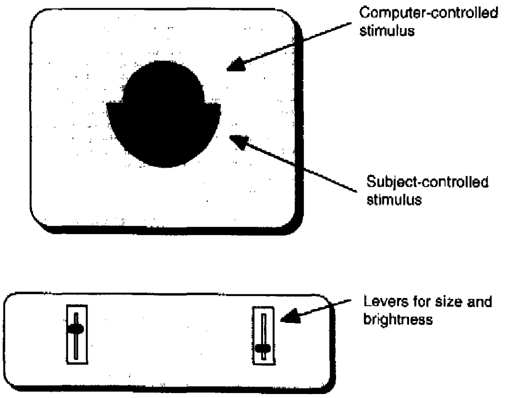

Fig. 6.1: The Continuous Monitoring Task (CMT).

The computer-controlled half-circle was modified continuously in real time on the two dimensions, size and brightness. The modifications of each of the two dimensions occurred randomly, discretely, and unpredictably. Furthermore, the changes sometimes occurred in synchrony, that is, changes in size and brightness occurred simultaneously, or the changes occurred in temporal succession, that is, with a time lag. Whether the changes occurred in synchrony or in succession at any point in time was unpredictable as well.

Participants were instructed to continuously adjust either one (i. e., 1D task) or both (i. e., 2D task) of the two dimensions, size and brightness, of the participant-controlled half-circle to isomorphic changes in the computer-controlled half-circle. In essence, thus, participants' task was a one-dimensional or a two-dimensional tracking task. Adjustment of the participant-controlled half-circle was achieved via two levers, one for size, one for brightness, that could be moved continuously. Both the changes in the computer-controlled stimulus and the responses made by the participants were continuously assessed by the computer and stored for analysis.

Two additional characteristics of the CMT are important. First, the computer-controlled stimulus always changed on both dimensions, size and brightness, even when participants' task was a one-dimensional tracking task. This was done to ensure that differences between participants' one-dimensional and two-dimensional performances would not reflect differences in the amount of perceptual information that was available in the computer-controlled stimulus.

Second, to make certain that individual differences in perceptual discrimination thresholds would not affect performance comparisons across age, the amount by which size and brightness changed was individually adjusted for both the computer-controlled and the participant-controlled stimuli. The adjustments were based on individual discrimination thresholds that were determined earlier in the same experiment with the same stimulus materials.

6.4.2 The Measurement of Monitoring Accuracy

Given the continuous nature of the CMT, participants' performance can, in principle, be assessed both at a macro and a micro level. At a macro level, and this will be our focus in the present chapter, participants' performance was assessed in terms of the absolute difference between the size or brightness level of the computer-controlled stimulus and the size or brightness level of the participant-controlled stimulus. More precisely, monitoring accuracy was computed as the time integral over the difference between the computer-controlled and the participant-controlled stimulus, scaled against a random baseline such that individual accuracy could vary between 0% and 100%. Zero% reflected chance performance and 100% reflected perfect synchrony with the computer-controlled stimulus at all times. Of course, due to participants' need to respond after the computer-controlled stimulus had changed, perfect synchrony could never be achieved. Even our best participants were not able to surpass the 90% accuracy level.

Two independent variables were manipulated in the context of this task. First, as mentioned above, participants were asked to either monitor size and brightness in isolation (1D task) or concurrently (2D task). Second, we manipulated the average time duration for which any particular size or brightness level of the computer-controlled stimulus remained on the screen before it was replaced by the next size or brightness level. To participants, this manipulation "felt" like a speed-of-film manipulation. That is, short durations created the impression of a quickly changing stimulus; long durations created the impression of a slowly changing stimulus.

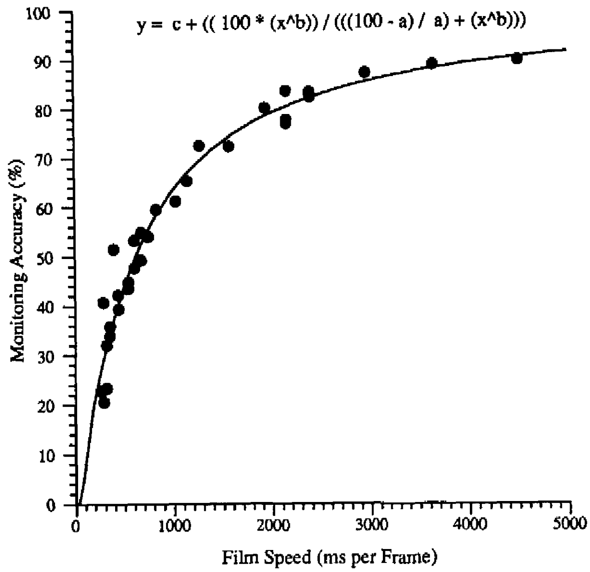

Fig. 6.2: Sample time-accuracy function for an individual participant.

The manipulation of frame duration allowed us to assess participants' monitoring accuracy across a whole range of fast and slow changing stimulus patterns, as shown in Figure 6.2. Therefore, the manipulation allowed us to compute individual time-accuracy functions. Individual data were fitted separately for size and brightness and 1D and 2D conditions to a hyperbolic power function using the CNLR procedure in SPSSX. Figure 6.2 shows an individual participant's level of monitoring accuracy as a function of the time duration between successive changes in the size dimension. As can be seen, performance is strongly affected by the time duration manipulation. At long time durations, corresponding to slow changes in the computer-controlled stimulus, the participant performed quite well, above 80%. At short time durations, corresponding to fast changes in the computer-controlled stimulus, the participant's performance was very poor. The integrals under the individual time accuracy functions, one of which is shown in Figure 6.2, were the basic units of analysis that will be referred to when the main empirical findings are summarized.

6.4.3 Design of Experiment

For the experiment, 79 participants from three different age ranges were recruited, children between eight and nine years of age, young adults between 20 and 25 years of age, and old adults between 65 and 70 years of age. Data collection took place over seven sessions. In the first session, a battery of intellectual ability measures was administered. In the second and third session, perceptual discrimination thresholds for size and brightness were determined for each participant. In sessions four and five, participants were instructed to adjust the two dimensions size and brightness in the CMT in isolation, that is, to perform the 1D tasks. Finally, in sessions six and seven, participants performed the size and brightness tasks concurrently, that is, in a two-dimensional situation.

6.4.4 Characteristics of Sample

Table 6.1 summarizes the basic characteristics of the sample (N = 69; data from 10 participants were discarded for various reasons) separately for children, young adults, and old adults.

Subjective Physical and Mental Health. Age differences in subjective physical health were significant only between children and old adults; for subjective mental health, children differed significantly from young adults.

Knowledge. In the vocabulary test, young and old adults performed better than children. For Spot-a-word, all three age groups differed significantly from each other.

Perceptual Speed. Young adults performed significantly better than children and old adults in both indicators of perceptual speed, the 'Identical Pictures' and

Table 6.1 Charakteristics of Sample

	Children (8–9) (*n* = 22)		Young Adults (19–25) (*n* = 23)		Old Adults (64–70) (*n* = 24)	
	M	*SD*	*M*	*SD*	*M*	*SD*
Age	8.4	0.5	21.8	1.7	67.2	2.0
Subfektive						
physical health[a]	1.5	0.6	2.0	0.6	2.3	0.9
mental health[a]	1.5	0.5	2.2	0.7	2.0	0.9
Knowledge						
Vocabulary	8.2	3.0	23.9	4.5	24.9	4.4
Spot-a-Word	5.9	4.4	20.3	8.1	26.3	6.1
Perpetual Speed						
Identical Pictures						
23.9	2.1	30.9	2.9	24.3	3.3	
Digit-Symbol Sub.	28.7	5.3	61.4	10.0	44.7	8.6
Thresholds for[b]						
Size	9	2.4	5.8	1.2	6.3	1.2
Brightness	21	3.3	17.8	3.4	17.9	3.6

[a] This was scored with a Likert-type scale ranging from 1 (excellent) to 5 (very poor).

[b] Individually determined in sessions 2 and 3.

'Digit-Symbol Substitution Test'. In the 'Digit-Symbol Test,' older adults performed significantly better than children.

Sensory Thresholds. Children differed significantly from young and old adults in their sensory thresholds for size and brightness (higher thresholds). However, there was no significant difference between young and old adults.

6.4.5 Main Findings

Figure 6.3 shows the mean performance in each age group on the CMT, separately for the one-dimensional and two-dimensional conditions. Depicted are the integrals under the average time-accuracy functions in each age group. In the 1D situation, shown in the left panel of the Figure, young adults performed better than old adults, who in turn, performed better than the children. For the 2D situation, shown in the right panel of Figure 6.3, the same rank-order applied, except that now the performances of children and old adults were no longer different.

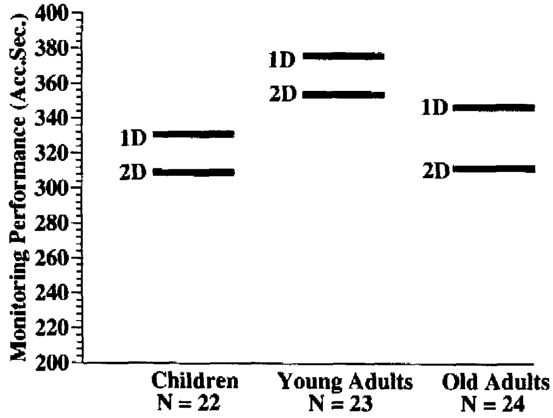

Fig. 6.3: One-dimensional (1D) and two-dimensional (2D) performance on the CMT for children, young adults, and old adults.

Figure 6.4 displays the difference between performance on the one-dimensional and the two-dimensional task separately for the three age groups. The 1D minus 2D performance difference is taken here as a global measure of the ability to learn, i. e., to form internal rules of behavior, in a situation where environmental change is unpredictable. We use the difference score rather than "raw" performance on the 2D task as a global measure of this ability because in the difference score individual differences in perceptual ability, motor speed, etc. are removed. It is important to note that the difference score is inversely scaled. That is, the smaller the score, the better the participant is capable of dealing with the unpredictable environment, thus, the better the participant's ability to learn.

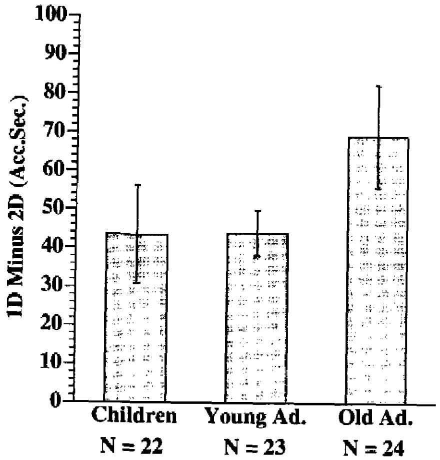

Fig. 6.4: Age differences in the ability to form internal rules of behavior, defined as difference in performance on the one-dimensional (1D) and two-dimensional (2D) task.

What Figure 6.4 conveys is that the overall difference between 2D and 1D performance, interpreted here as a global measure of learning under conditions of low environmental predictability, does not differ for the children and the young adult group. However, both of these age groups exhibit smaller overall scores than the old adult age group. Thus, it appears that children and young adults are better at dealing with the unpredictable environment than are old adults; by inference, children and younger adults are thus able to learn better under conditions of low environmental predictability than old adults.

One might argue that the differential learning that is captured by this finding might simply be a reflection of a differential speed deficit. According to this explanation, old adults would show decreased learning because their processing speed is much slower than that of young adults. Children would not show this deficit, so the argument could go, because they do not differ in processing speed from young adults. That this explanation is unlikely to be correct is shown in Figure 6.5.

Figure 6.5 displays the performance of the children and the old adult group relative to the performance in the young adult group. The bars in Figure 6.5 capture the deviation of the children and old adult groups from the performance of the young adults group on three dependent measures: performance on the one-dimensional CMT, 2D minus 1D performance on the CMT, and performance on measures of fluid intelligence. If we use performance on the one-dimensional monitoring task as a proxy measure for processing speed, we find that children, in fact, perform worse than older adults on processing speed; yet, they show smaller 2D minus 1D scores than older adults.

It thus seems that the ability to form internal rules of behavior under conditions of low environmental predictability does indeed change across the life span, as has been anticipated by our discussion of age-related changes in cognitive control in

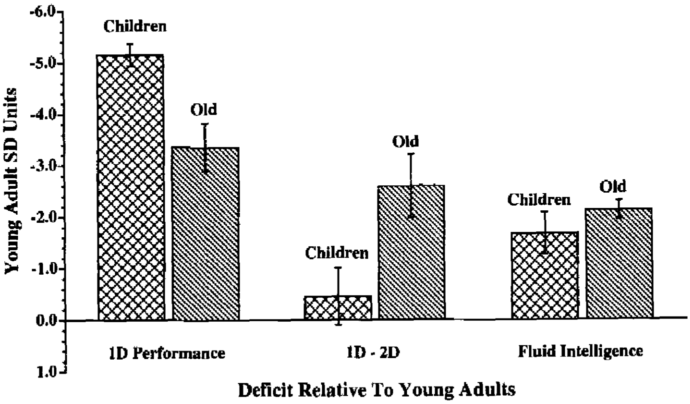

Fig. 6.5: The performance of children and old adults is expressed as standard deviation units of the young-adult performance on the 1D task, 2D minus 1D performance, and fluid-intelligence composites.

the previous section. However, the changes in learning ability appear to be more pronounced between the ages of 25 and 70 than between the ages of 8 and 25.

In the next section, we consider whether learning ability under conditions of low environmental predictability may be related to age-related changes in general cognitive functioning as assessed by measures of fluid intelligence. First, we briefly discuss the age-gradient of fluid intelligence. Then, we present findings obtained with the CMT that empirically assess the relation between age differences in learning and age differences in fluid intelligence.

6.5 Are Age Differences in Fluid Intelligence Predictive of Age Differences in the Ability to Generate Rules of Behavior under Conditions of Low Environmental Structure?

Some of the best-documented findings in the literature on cognitive development and aging are age-related differences in fluid intelligence (5; 7; see also 88–90), Type A cognition (28), or the mechanics of cognition (3; 4). Fluid intelligence refers to an individual's capacity to organize information, to ignore irrelevancies, to concentrate, and to maintain and divide attention. Age-related differences in fluid intelligence are found with a wide variety of memory, reasoning, and spatial abilities measures.

Perhaps the most widely used marker test of fluid intelligence is the Raven's Advanced Progressive Matrices test (APM; 91–93). This test is known to be a good index of general intelligence. For instance, in radex models of ability organization, the Raven's falls very close to the centroid of general intelligence (94).

Each item in this test consists of a matrix of geometric patterns. Participants are instructed to determine the relations among elements in the rows and the columns, and to select the pattern that best completes the matrix.

Performance on the Raven's has been found to steeply increase during middle childhood and adolescence, and to gradually decrease thereafter (see Figure 6.6). The link between age and fluid intelligence has been consistently demonstrated since at least the 1920s (91; 95; 96), and is readily apparent in many results from standardization data in psychometric and neuropsychological test batteries. Given that (a) the samples used for standardization are typically large and representative, (b) the performance measures are of established reliability and span a broad range of cognitive abilities, (c) negative adult age trends have been observed both with cross-sectional and longitudinal sampling schemes, and (d) adult age differences on tasks related to fluid intelligence are especially large at asymptotic limits of performance (97), the general phenomenon of a link between age and fluid intelligence must be considered robust.

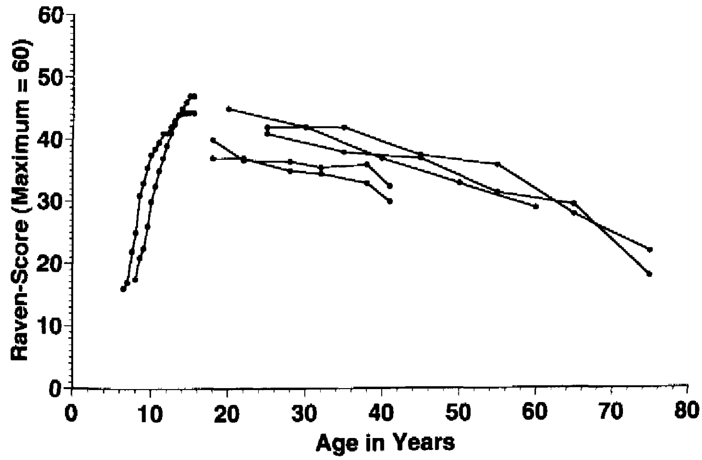

Fig. 6.6: Age gradients for the Raven's Advanced Progressive Matrices Test. Each set of interconnected data points refer to a large cross-sectional reported in Salthouse (1991) or Raven (1989).

Age-related differences on tests of fluid intelligence are not only meaningful because they can be demonstrated reliably. They are also meaningful because performance on these tests has been shown to predict performance outside the laboratory and in non-academic settings (e. g., 98–100). Although the relation between performance on test batteries and performance outside the laboratory is not perfect, it has been shown to be significant and of at least moderate size.

In the last, very brief, part of this chapter, we summarize empirical findings obtained with the CMT that directly address the question to what extent, if at all, old-age differences in rule formation ability are predicted by age differences in fluid intelligence.

In order to address this question, we performed a series of hierarchical regression analyses on the data described in section 6.3 of this chapter, followed by communality analyses. This analysis allows us to determine how much of the age-related difference in the ability to learn under conditions of low environmental structure is due to the unique and shared influence of age-related change in (a) processing speed and (b) fluid intelligence, when processing speed is indexed by performance on the one-dimensional CMT, and fluid intelligence is indexed by performance on the Raven's. Given that we did not obtain an age difference in learning ability for the children and the young adult group, this analysis is, by necessity, limited to the empirically obtained difference between the young and old adult age groups.

When partitioning the positive terms of age-group differences in learning ability, we find that 48.9% of the age-related variance was uniquely predicted by age group, 37.6% by age group and fluid intelligence, and 13.5% by age group, fluid intelligence, and processing speed. The unique term for age-group differences in learning ability related to processing speed was negative, indicating that processing speed is more strongly related to learning ability when the other predictors are present in the regression equation than when it is considered as the only predictor.

These findings demonstrate that the ability to form rules of behavior in the absence of environmental structure is predicted, to some extent, by age-related differences in fluid intelligence, above and beyond the influence exerted by processing speed.

A qualitatively very similar pattern of results is obtained when we use two measures of perceptual speed, rather than performance on the one-dimensional monitoring-task, to index processing speed. Although the numbers change, the pattern of results stays the same: young and old adult group differences in learning ability are predicted by age group differences in fluid intelligence.

By negative implication, these results suggest that the ability to learn, i. e., to generate rules of behavior, under conditions of low environmental predictability, develops relatively early in life (e. g., before the age of eight). According to a life-span dissociation hypothesis, positive age changes in fluid intelligence during middle childhood and adolescence may be related predominantly to factors other than learning (i. e., rule formation) ability, such as processing speed (101) or knowledge acquisition. In contrast, age-based reductions in fluid intelligence are more general in kind, and may also involve learning ability. This hypothesis is also consistent with evolutionary considerations in the context of life-span theory (102). Currently, further empirical work, including micro-analyses of monitoring performance, testing-the-limits through extensive practice, and more direct assessments of relevant component processes are underway to test the tenability of this hypothesis.

6.6 Summary and Conclusions

At the beginning of this chapter, we argued that learning is typically defined in terms of an organism's ability to modify its own internal Knowledge Structure in order to accommodate internal and/or external demands, and that indeed, most existing research on human and animal learning is concerned with how organisms come to internally represent systematic structural features of the environment. However, humans at least are also capable of dealing with unpredictable, unstructured environments in highly systematic ways; that is, they are capable of modifying their internal Knowledge Structure even in the absence of environmental systematicity. Our main focus in the present chapter has been on the human ability to learn, that is, on the ability to form internal rules of behavior under conditions of low environmental structure. More specifically, our focus has been on potential ontogenetic changes in the human ability to generate internal rules of behavior.

In the first part of the chapter, we examined whether there is theoretical reason to suspect that the ability to form rules of behavior when the environment is unpredictable may change with age. We first discussed the psychological reality of the cognitive control concept, and showed, on the basis of both psychological and neuropsychological evidence, that the control of one's processing is functionally separable of the processes that are controlled. Then, we summarized existing research in the areas of cognitive development and cognitive aging that demonstrates that cognitive control ability may diminish with increasing age. These findings imply the possibility of ontogenetic changes in the ability to generate internal rules of behavior under conditions of low environmental structure. We introduced a new experimental paradigm that can be used to investigate age differences in the ability to generate behavioral rules, and described the results of an initial experiment with this paradigm.

Based on our empirical findings, we argued that the ability to form internal rules of behavior under conditions of low environmental predictability does indeed change across the life span, as had been anticipated by the discussion of age-related changes in cognitive control. However, the changes in learning ability appeared to be more pronounced between the ages of 25 and 70 than between the ages of 8 and 25.

We then discussed the age gradient of general cognitive functioning, as captured by measures of fluid intelligence, and empirically demonstrated that age differences in the ability to generate rules of behavior are predicted by age differences in measures of fluid intelligence.

Taken together, the theoretical analysis and empirical findings presented in this chapter should be viewed as a first step toward trying to understand and disentangle the complex relation between properties of the information-processing system and the human organism's ability to form consistent rules of behavior when the environment is unpredictable. It will be fascinating to work out in detail which rules of behavior are optimal for a given information-processing system, but then, this step, if indeed it will ever be achieved, will need to be the focus of a different chapter ...

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