Multiple-task Performance and Aging

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Proefschrift

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door

Johan Egbert Korteling

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Promotores:

Prof. dr. G. Mulder
Prof. drs. J. Moraal

1. Psychologische modellen die aansluiten bij bestaande neurobiologische kennis verdienen de voorkeur boven modellen die dat niet doen. Met de neurobiologie *strijdige* modellen zijn op zijn best quasi-wetenschappelijke data-fitters.

    (Dit proefschrift)

2. Psychologische theorieën waarin, als verklarend construct, een centrale verwerkingseenheid is opgenomen met functies zoals: sturen, controleren, superviseren en organiseren, zijn triviaal, verklaren niets en leveren geen accumulerende kennis op.

    (Dit proefschrift)

3. Beperkingen in de informatieverwerkings-capaciteit worden bepaald door de wijze waarop het zenuwstelsel voldoet aan twee tegenstrijdige eisen: hoge associatieve verwerkingscapaciteit en flexibiliteit enerzijds en samenhang en doelgerichtheid in het gedrag anderzijds

    (Dit proefschrift)

4. De term *selectieve aandacht* is een pleonasme.

    (Dit proefschrift)

5. Bij het uitvoeren van dubbeltaken hebben ouderen problemen met het integreren van samenhangende deelvaardigheden en met het separaren van niet-samenhangende vaardigheden die op elkaar lijken.

    (Dit proefschrift)

6. Ouderen hebben meer problemen dan jongeren met het veranderen van vaardigheden.

    (Dit proefschrift)

7   Al is er maar een minimale kans is dat er de komende eeuw een allesvernietigende wereldoorlog uitbreekt, dan is er voor de aarde een katastrofe gaande.

8   Het alles-overheersende belang dat binnen ons rechtssysteem wordt gehecht aan het *rechtszekerheid principe* leidt noodzakelijk tot maatschappelijke rechtsongelijkheid gepaard aan een dik-belegde boterham voor juristen.

9.   Positieve discriminatie is onrechtvaardig omdat statistische verschillen tussen groepen worden vereffend op individuen, voor wie deze verschillen irrelevant zijn.

10.   De overweldigende schade die door het autogebruik wordt aangericht aan de leefomgeving, i.e. lucht, flora, ruimte, geluid en uitzicht, zou betekenen dat de maatschappij eerder melkkoe is van de auto, dan andersom.

11.   De onnodig lage wisselfrequentie van de meeste langs de openbare weg geplaatste digitale tijd/temperatuur displays levert, door het uitlokken van lange observatietijden, een serieus gevaar op voor de verkeersveiligheid.

12.   Gezien de problemen die veel (oudere) mensen hebben met het reproduceren van hun pincodes is het onbegrijpelijk dat, althans bij de Postbank, de cijfers op verschillende pincode-apparaten een verschillende ruimtelijke configuratie hebben.

13.   Filmregisseurs zouden rekening moeten houden met het feit dat zelfs ervaren acteurs niet in staat zijn met hun ogen vloeiende volgbewegingen te maken als er geen bewegende *target* wordt gepresenteerd.

14.   Het leven van een psychonoom vergt veel geduld, tact en zelfbeheersing; zijn kennis betreft een nogal omvangrijk deel van het dagelijks bestaan waarvan iedere leek meent méér verstand te hebben.

Voor mijn vader en mijn moeder

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Voorwoord

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Chapter 1

Introduction

1.1 Practical background

In the last decades, our society has rapidly changed from an industrial society to an informational society. Examples are associated with industrial robotics, flexible manufacturing systems, computer-assisted design and manufacturing, advanced communication systems, and office automation. These kinds of technological developments have altered the nature of jobs and tasks. Individuals have become controllers of energy, instead of sources of energy (McDowd, Vercruyssen, and Birren, 1991). In many work situations, operators are required to monitor, control, and manipulate information via complex technological systems. Such systems typically involve performance of several tasks in a limited period of time. Hence, social and professional maintenance has become more dependent on perceptual-cognitive skills than on physical strength. Impaired attentional capacities may make workers highly susceptible to errors or accidents. Such problems in particular involve elderly people.

The decrease of both birth and death rates that have occurred in the industrialized countries have produced populations that are significantly older than in previous periods. In the year 2000, more than 20% of the populations of these countries will be 60 years and older, while the most rapidly growing group is that of people over 80 years. In addition, an increasing number of older persons reinforce the recent trend toward an elderly population living alone in separate households, independent of relatives and institutions. In this connection, it is relevant that aging in adulthood is accompanied by psychomotor decline (see Welford, 1977a, for an overview). This decline is reflected in daily life, in which sooner or later older people find difficulty either in fulfilling their jobs or doing activities in and around the house. Therefore, it is important to create a living and working environment that affords efficient and comfortable functioning of elderly people, such that men and women in later life can maintain their functional independence, well-being, and self-respect as long as possible.

However, insufficient research has been done on interfacing new technologies with the aging part of the population. Moreover, a valid theoretical framework for this kind of research is still lacking. Therefore, more knowledge with regard to complex-task performance is needed based on which technical products, processes, and systems involved in daily life of older people can be matched to their capabilities and needs.

When functional capacities deteriorate, one of the major factors determining whether or not an elderly person can remain in his own home or needs to seek institutional care is his remaining degree of mobility (Smith, 1990). Therefore, having access to good transportation facilities is a key to an active and healthy old age. In contemporary society, having an private automobile has become the main determinant of the degree of mobility (U.S. Department of Transportation, 1986). When people are enabled to drive an automobile on their own, their functional independence will be substantially increased. Consequently, their demand for expensive professional help will be delayed. Automobile driving, however, is a complex task in which different subtask have to be performed simultaneously. This may involve control of the pedals, the steering wheel and the gear, while at the same time the road environment and the behavior of other traffic participants have to be monitored.

The driving task should be adapted as much as possible to the capabilities and limitations of the older driver population. Possible contributions to this could come from human factors analysis of the driving task and from the development of better design principles and new technologies to reduce the implicated perceptual, decisional and motor complexities. In this connection, the present thesis is focussed on theory development with regard to multiple-task performance and the development of general theoretical principles concerning aging-related problems in complex psychomotor tasks such as driving.

Since aging is a gradual process, progressing along many different dimensions, it is impossible to provide a consistent, universal, and valid definition of the concept of *old age*. Therefore, in the present thesis, aging will be regarded just as a compound statistical phenomenon related to chronological age in adulthood, becoming sufficiently powerful for behavioral applications by about 60 years of age or older.

1.2 Outline of the study

The purpose of the present thesis is to explicate some difficulties with regard to the fundamentals of human performance theory and to provide some improvements for this theory. In brief, the issue may be summarized as a lack of conceptual depth needed to acquire *accumulating* knowledge concerning the *underlying mechanisms* determining performance in complex psychomotor tasks and the performance deteriorations of older adults in these tasks.

This thesis consists of two parts. Part One focusses on the state-of-the-art of multiple-task performance theory and endeavors to develop foundations for a theoretical framework which better incorporates training effects and current knowledge concerning brain functioning. The objective of Chapter 2 is to review the main contemporary theories concerning multiple-task performance. In Chapter 3, these theories will be critically evaluated. In Chapter 4, a new framework is proposed, starting from existing

knowledge concerning brain functioning and human performance in dual tasks. The final chapter of Part One places this theory development in an aging-related perspective and outlines the rationale of the experiments. These experiments are described in more detail in the subsequent chapters, which make up Part Two of this study. Both parts contain their own list of references.

Chapter 2

Capacity theories

2.1 Introduction

Many skilled typists can carry on a conversation while typing from copy and many skilled musicians can do the same while playing their instrument (if it is not a wind instrument). Also in everyday skills, practiced subjects can do what seems almost impossible to the novice. For inexperienced drivers, control of an automobile requires full attention. Later, the practiced driver can turn, take over, deal with right of way situations at intersections, and shift gears while listening to the radio or debating vigorously any topic of interest. However, when an emergency situation looms up, the conversation may be halted for a while and be continued when the situation is handled.

How do we perform complex tasks requiring two or more activities in a short period of time and what determines the quality of performance? Psychological theories concerning multiple-task performance suppose that several mechanisms determine success or failure in coping with problems. Of course, adequate scheduling of time devoted to the various activities and efficient switching between them, is a crucial determinant of success and failure. However, if the time needed for the separate subtasks exceeds the total time available—for example, when two 10-minute tasks have to be performed in 15 minutes—a person is enforced to *time-share* both subtasks, i.e., one has to engage in concurrent processing. In such a case, several other mechanisms are supposed to come into play. At present, theory formation has been mainly focussed on *competition for scarce processing resources* and *automaticity development* on the basis of extended training. Also, phenomena resulting from the interaction of subtasks have been described, such as: *integration*, *coordination* and *combination* of task processes, and *confusion*, *interference*, or *cross-talk* between subtask elements. These latter kinds of phenomena have not yet been placed into a solid theoretical framework.

The present chapter will introduce the main current theories concerning multiple-task performance, along with some direct empirical problems. These theories generally are based on the notion that human performers possess one or a few fixed energetic resources with a limited capacity (sometimes called the 'fuel metaphor'). Therefore, they are labeled *capacity theories*.

2.2 Single-resource theory

In dealing with measurement and analysis of workload of human subjects in multiple-task situations, several authors start with a simple and straightforward model of the actor as possessing a single "pool" or supply of aspecific limited-capacity resources, or as possessing a general central limited-capacity information processor (e.g., Broadbent, 1971; Kahneman, 1973; Knowles, 1963; Moray, 1967; Norman and Bobrow, 1975). According to these authors, *one unspecific energetic input of limited availability* is required by all processing structures and thus by all tasks. In time-sharing tasks, this underlying commodity can be distributed in graded quantities over subtasks, depending on subtask difficulty or demand (allocation strategy). Therefore, the degree to which two simultaneous tasks interfere is determined by the amount of capacity they use from the same single source of energetic input. For example, when one task becomes more easy, or better trained, it will demand fewer resources, and thus more capacity will remain available for a concurrent task. Although some authors (e.g., Kahneman, 1973) assume that capacity grows or shrinks as a function of task demands, the upper limit of the available resource volume typically is assumed to be fixed. Moreover, subjects are assumed to dedicate their resources totally to task performance. Hence, unless intentionally varied, the total of available and fixed resource input is considered to be allocated in task performance (Gopher and Sanders, 1984).

The single-capacity concept conjectures the underlying energetic entity to be *undifferentiated*, which means that all tasks depend on this scarce input entity. This leads to testable predictions. One prediction is that increasing the difficulty of one task, presumably consuming more resources (as allocation is held constant), should affect the performance of the other task. In a number of studies, such difficulty manipulations failed to degrade performance of a second task (e.g., North, 1977; Kantowitz and Knight, 1976; Wickens, 1980 for a summary of such studies) which was termed *difficulty insensitivity*. In addition, several authors have demonstrated *perfect time-sharing*, that is, subjects can perform the subtasks (of non-trivial difficulty) of a dual-task in combination as well as they can perform either task separately (e.g., Allport, Antonis, and Reynolds, 1972; Shaffer, 1975: see Wickens, 1991). Other phenomena, which cannot be explained by single-resource conceptualizations, are *structural alteration* and *difficulty-structure uncoupling* in which the degree of interference of tasks is predicted not by their difficulty but by their structure (see Wickens, 1984, 1992 for reviews). In this connection, the term structure refers to the manner of information processing that is required by a task, such as spatial or verbal. For example, Wickens (1976) showed that a manual tracking task may be more disrupted by a concurrent open-loop force generation task than by an auditory signal detection task, although the latter was assessed to be more difficult, and therefore may be supposed to demand more resources. Although difficulty insensitivity and perfect time-sharing may be explained in some instances by data limits in the tasks

(Wickens, 1984, 1992), collectively these phenomena are not consistent with a single-resource conception of human attention.

In conclusion, experimental evidence seems to be more consistent with a conception that takes into account the segregated character of the human information processing system. A major step in this direction was the formulation of multiple-resources theory.

2.3 Multiple-resources theory

In order to account for the phenomena of perfect timesharing, difficulty insensitivity, structural alteration, and difficulty-structure uncoupling, the concept of multiple-resources was invoked (Kantowitz and Knight, 1976; Navon and Gopher, 1979; Wickens, 1980). The multiple-resources concept is also based on the assumption of a fixed limited internal input dedicated to the task. However, this input is not regarded as a single, unspecific entity, but as a differentiated entity. According to this view, people have several different capacities with resource functions.
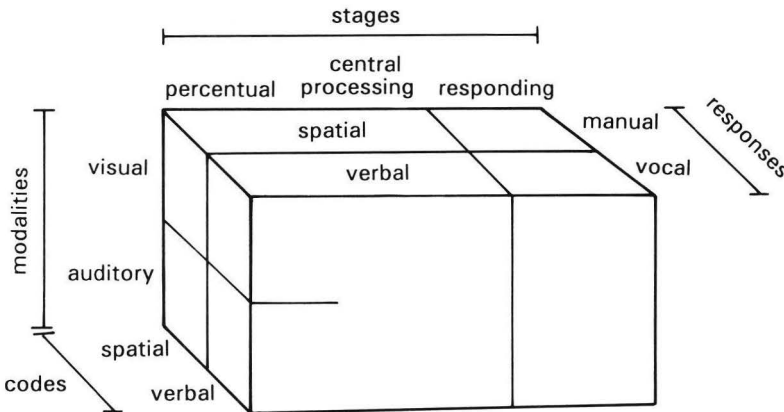
Fig. 2.1 The structure of multiple-processing resources proposed by Wickens (1984) in R. Parasuraman and R. Davies (Eds), *Varieties of Attention*, New York: Academic Press.

On the basis of an analysis of subtask characteristics and interference effects in a large number of dual-task studies, Wickens (1980, 1984, 1989, 1991, 1992) postulated a model consisting of three dichotomous dimensions (Figure 2.1). The dimension of processing *stages* contrasts two resources, one associated with perceptual-cognitive processes and one associated with response processes. The second dimension contrasts two *codes* of information processing: spatial *vs* verbal information processing. The third dimension

involves input *modalities*, i.e., visual *vs* auditory. In general, tasks will interfere more, and difficulty-performance trade-offs will be more likely to occur, if more levels on these three dimensions are shared. According to Wickens (1991), the dichotomies of stages and codes have been shown to be compatible with structural and energetic systems. By way of the additive factor logic, in choice reaction tasks, independent arousal or activation effects of stressors such as sleep-loss or time-on-task and psychoactive drugs on perceptual-cognitive and response processes have been shown (Frowein, 1981; Gopher and Sanders, 1984; Sanders, Wijnen, and Van Arkel, 1982). It is also well-known that the right and the left cerebral hemisphere are associated with different kinds of information processing and action control (e.g., Friedman and Polson, 1981; Hellige and Longstreth, 1981; Hellige, Cox, and Litvac, 1978; Polson and Friedman, 1988; Kinsbourne and Hicks, 1978; Luria, 1973). For example, resources underlying spatial processing and left-hand control are predominantly localized in the right hemisphere, and resources underlying verbal functions and right-hand control are conceived to reside more in the left one. Based on re-analyses of some of the old data, Wickens (1991) is reluctant to maintain the dichotomy of visual and auditory input, which seems not to be associated with such energetic systems.

It has been assumed that if demands on one resource are sufficiently strong, resources from another pool may be applied to the demanding task, albeit with reduced efficiency (Navon and Gopher, 1979). When this takes place in a task depending on the left-hemisphere task combined with a right-hemisphere task, such process was termed *hemispheric overflow* (Hellige and Cox, 1976). This idea that resources mechanisms instantly can take-over mutual functions is difficult to defend when one takes into account the chronic character of effects of brain-damage, i.e., the slow, effortful and incomplete recovery of function in most adult patients suffering from focal brain-damage (probably involving some functional overtake, but also regeneration and sprouting). Such ideas, assuming relocatability of information processing in the brain, are associated with the so-called *computer fallacy*, which will be discussed in § 4.2.

On a longer time-scale, however, the pattern of resource dependency of a task may change. Novice typists, for example, rely heavily on visual information concerning the keyboard, whereas in skilled typists, proprioceptive information becomes (relatively) more important and the dependency of visual information in finding the right buttons decreases. According to multiple-resource theory, this enables the skilled typist to divert more visual attention to the reading subtask.

It is generally recognized that extended training may produce impressive improvements, in single-task as well as in dual-task performance. How can this be explained when fixed capacity is supposed? According to Schneider and Detweiler (1988), multiple-resources theory generally has not been applied to practice effects. Within a fixed-capacity framework, training effects in single- and dual-task performance are most

markedly captured by *dual-process theory*. This theory, which is discussed below, also deals with the varying degrees of time-sharing efficiency with which different task combinations may be performed.

2.4 Automatic and controlled processing

The general idea invoked to explain training-related performance variations with fixed capacity is that after training, the same limited processing resources becomes more *efficiently* used. Two mechanisms are conjectured that may be responsible for increased efficiency as a function of experience. Efficient task performance may be a caused by a more *automated* (James, 1890; Bahrick and Shelley, 1958), and thus less resource consuming, performance of the component tasks (e.g., Logan, 1978; Schneider and Shiffrin, 1977). This notion applies to single- as well as dual-task performance. In addition, with respect to dual-task performance, *unique time-sharing skills* may be developed (e.g., Damos and Wickens, 1980; Schneider and Detweiler, 1988).

The first hypothesis explaining practice-related performance variations with fixed capacity is based on a rediscovery of an old distinction (James, 1890; Bahrick and Shelley, 1958) between two modes of information processing (e.g. Detweiler and Schneider, 1991; Fisk, Ackerman, and Schneider, 1987; Fisk and Rogers, 1991; Logan, 1978; Posner and Snyder, 1975; Schneider and Shiffrin, 1977; Shiffrin and Schneider, 1977, 1984), which mostly are referred to as *automatic* and *controlled* processing. Automatic processing does not depend on attention. It is fast, parallel, effortless, not under direct subject control, does not suffer from or cause interference, is not limited by short-term memory capacity, and does not necessarily give rise to conscious awareness (pre- or postattentive). It usually is regarded as an important contributor to well-developed skilled behavior, but it only develops when tasks are characterized by an invariant relationship between stimuli and responses, i.e., *consistent mapping*. Automatic processing is under the control of stimulation; once learned, it is difficult to suppress, modify, or ignore. Finally, it is thought to be relatively invulnerable to individual differences, such as aging or brain damage. In contrast, controlled processing is generally regarded as relatively slow, serial, effortful, limited by short-term memory capacity, subject-controlled and is based on general resources in order to deal with novel or inconsistent stimulus-response relations (varied mapping). Controlled processes are under the control of intentions (strategies, expectancies, plans) of the subject and depend on attention; responses thus are easily modified, suppressed, or ignored. In tasks requiring controlled processes a wide range of individual differences may be seen. It should be noticed that not all of these criteria are generally accepted by different authors (e.g., Bargh, 1992; Cohen, Servan-Schreiber, and McClelland, 1992; Neumann, 1984; Logan, 1992).

Following this dual-process theory, automatically performed processing operations do not, or to a lesser degree, draw on limited attentional capacity, whereas controlled processes are subject to substantial limitations on attentional capacity (e.g., Schneider and Fisk, 1982; Logan, 1990). Improvements in dual-task performance may therefore result from the development of automatic processing, producing reduced resource demands of the task as a whole. For example, using a visual target-detection paradigm Schneider and Fisk (1982) have shown that automatic and controlled processing can be carried out jointly without costs. According to these authors there is no fixed attentional capacity limitation for dealing with consistent task components because, after sufficient training, these components become independent of this capacity. However, joint controlled processing cannot be done without deficit. A fixed upper bound to processing capacity is assumed as far as a task requires controlled processing.

This automaticity hypothesis may be able to explain training-related performance differences assuming fixed capacity. That is, with a fixed resource availability, the degree of automaticity in task performance will (among other things) determine the factual *scarcity* of this input and thereby the quality of dual-task performance. As such, increased automaticity works the same as decreased task difficulty. Accordingly, differences between trained and untrained performers can be accounted for within a fixed-resource framework.

2.5 Time-sharing skills

In order to incorporate effects of practice in multiple-tasks performance into a processing theory based on fixed limited capacities, it has also been suggested that practice may result in the development of new true time-sharing skills. This means that some component of performance gain is not due to automaticity in single-task performance. Extended practice may result in a general or specific time-sharing ability, allowing people to more efficient time scheduling, to more rapid alternation of attention between tasks, and/or to develop optimal resource allocation strategies. (e.g., Broadbent, 1954; Damos and Wickens, 1980; Gopher and Brickner, 1980; Schneider and Detweiler, 1988; Schneider and Fisk, 1982). Unique time-sharing skills are mostly treated as capacity phenomena, i.e., representing an increased *efficiency* of resource consumption (e.g., Wickens, 1992). That is, more efficient or coordinated performance of constituent subtasks in combination may result in reduced demands for resources of the dual-task as a whole. Unique time-sharing skills may be demonstrated in various ways (e.g., Damos and Wickens, 1980): 1) by showing transfer of developed skills in one dual-task to another qualitatively different dual-task; 2) by demonstrating higher training benefits with dual-task practice than with single-task practice; 3) by demonstrating through detailed

performance analysis that training produces changes in strategy that reflect differences in the manner in which subtasks are interwoven or combined.

At present, the data concerning this hypothesis appear rather tentative. Damos and Wickens (1980) showed positive transfer of training of a dual-task consisting of a short-term digit memory task and a digit classification task to a dual-task consisting of two identical one-dimensional compensatory tracking tasks. In addition, more detailed analysis of dual-task performance in both task pairs indicated that dual-task training resulted in parallel processing, which transferred between task combinations. The amount of transfer between different time-sharing tasks, however, was rather small relative to the total increase in task performance. Gopher and Brickner (1980) demonstrated that subjects, who were trained in a time-sharing strategy that successively emphasized different resource allocation policies became more efficient time-sharers in general than did a group trained only with equal priorities. Schneider and Fisk (1982) showed that subjects can learn to employ an optimal time-sharing strategy by emphasizing the varied mapping (controlled) task and allocating attention away from the constant mapping (automatic) task. This experiment showed that single-task automaticity *and* specific dual-task training can contribute to overall time-sharing efficiency. A brief review of Schneider and Detweiler (1988) concerning experiments aimed at interference effects between highly practiced tasks suggests that after extended (consistent) single-task training, still substantial dual-task training is required to reach single-task performance levels. Schneider and Fisk (1984), for example, found nearly novice-level dual-task performance after eight hours of single-task training (1755 trials) in digit and category visual search tasks. This finding substantiates the conclusion of Damos (1991) on the basis of the literature that, when training time is restricted, the greater part of the training should be conducted under dual-task conditions.

Based on the foregoing data it is, according to Wickens (1992, p. 385), safe to conclude: *...that the very efficient time-sharing performance of the expert results not only from the more automated performance of component tasks but also from a true skill in time-sharing .....To what extent the time-sharing skill acquired in one environment is generalizable to others is not well-established.* Hence, next to automaticity, acquired time-sharing *skills* may lead to efficient time-sharing performance, i.e., enhanced task performance with the same amount of resource inputs. However, the amount of transfer between different time-sharing tasks sometimes appears rather small relative to the total increase in task performance (e.g., Damos and Wickens, 1980). This leads to the overall conclusion that learned time-sharing skills are rather specific for the given task combination.

Wickens' statements concerning specific time-sharing skills should not be considered compatible with the *attention-is-a-skill* hypothesis (Hirst et al., 1980; Spelke et al., 1976)[1]. This hypothesis states that the development of skills with training imply alteration of an underlying structural mechanism resulting in increased input capacity with reference to the trained task (see § 4.5). Wickens (1992) apparently conjectures the acquisition of unique time-sharing skills as the development of more *efficient* processes, which are specific for dual-tasks.

In Chapter 3, I will present some major objections against the fundamentals of capacity thinking—i.e., resource and dual-process theories—as explanatory frameworks for performance limitations in multiple-task situations.

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[1] In that case, Wickens' thinking would be inconsistent, that is, fixed capacity would be assumed with reference to his framework of resources, whereas variable capacity would be assumed when talking about unique time-sharing skills.

Chapter 3

A critical evaluation of capacity theories

3.1 Introduction

The central thesis of capacity theories stems from the year 1958, in which Broadbent published his book *Perception and Communication*. It is the assumption that limits of attention are caused by an *a priory* limited processing capacity of the brain that, just as any other physical system, has a fixed upper limit in available capacity. Broadbent based this limited-capacity assumption on a logical theorem in the mathematical theory of communication. The argument proceeds as follows. When the rate of information input to any finite channel exceeds a certain upper limit—called the channel capacity—not all of it can be transmitted without error. Because the brain itself is a finite physical system and because it transmits (or processes) information, there must be a limit to human capacity as well. According to Navon (1984) and Gopher and Sanders (1984), any explanation of variability of task performance that does not require this limited capacity assumption does not belong to resource theory.

The argument of Broadbent is valid in principle. The number of simultaneous stimuli and stimulus combinations that may reach the brain via all our sensory systems is very large and it is very hard to imagine that all available stimulus elements and configurations can be processed at one time. Therefore, in order to prevent overload, the system needs a selection mechanism. The upper limit of information processing capacity may thus be considered the direct physical basis for performance decrements in dual-tasks relative to single-tasks and for the selective nature of attention as well. In addition, the use of physical systems as a metaphor has great intuitive appeal.

However, as opposed to analogous physical constructs the resource construct, which also figures centrally in the dual-process theory, still has a vague and malleable connotation. This is demonstrated by the various usages and the manifold synonyms of the term ('capacity', 'input', 'attention', 'effort') and the absence of a general well-defined metric or definition for these kinds of entities. Introduction of the computer metaphor in cognitive psychology, ascribing behavioral capacity limitations to a kind of general-purpose central processor with a fixed capacity, did not resolve this problem. The seductive power and the flexible meaning of the construct is probably the main reason why people overlooked its hypothetical and allegorical nature, such that it escaped from criticism on empirical grounds for a long time (Navon, 1984). In the following paragraph,

I will discuss the major objections that may be raised against capacity theories. These criticisms will deal primarily with the basic, or fundamental, assumptions and characteristics of capacity theories. Resource and dual-process theories share some of these basic assumptions with regard to human information processing and are partly complementary to each other.

3.2 Direct empirical problems

There is at least one direct empirical problem with resource theories. Both proposed systems consisting of one or a few resources are too crude to explain the differentiated pattern of interference effects from dual-task experiments. Briefly, on the one hand there are cases of specific interference effects within a resource, while at the other hand effects may be less specific than what would have been expected on the basis of what are assumed to be independent resources.

With respect to specific interference effects, Klapp (1979), for example, found superior time-sharing in simultaneous rhythmic activities when temporal patterns were compatible and Peters (1977) showed that the magnitude of interference effects in two motor tasks decreased with the degree to which the concurrent rhythms could be made compatible. North (1977) found more interference between keypressing/keypressing or tracking/tracking than between keypressing/tracking. These kinds of results are far too specific to be accounted for by the degree to which subtasks compete for the proposed global resources. In principle, this problem could be handled by simply assuming new resources within resources for each specific kind of interference that may be found. However, on the basis of scientific parsimony, this cannot be justified, and most authors supporting the multiple resource notion are well aware of this (e.g., Navon, 1984; Wickens, 1991).

In contrast, quite unspecific effects have been found that seem not to depend on specific resources (e.g., Keele, 1967; Lindsay, Taylor, and Forbes, 1968; Schvaneveldt, 1969; Trumbo and Milone, 1971). These kinds of results are compatible with single-resource conceptions or can be accounted for by postulating one pool of general resources above the more specific resources. General superpools have been referred to as the *Central Executive* or the *Supervisory Attentional System* (Norman and Shallice, 1980; Baddeley, 1986). However, such conceptions easily ascribe the (really interesting) things to the so-called *homunculus* or *ghost-in-the-machine*, i.e., the little-man-in-the-head (see § 3.4.1). Multiple resource theories incorporating a "superresource", of course can explain many specific interference effects *and* every phenomenon of unspecific interference. Nevertheless, the theory will be weak because it cannot predict when specific or unspecific interference would occur.

With regard to the dual-process theory, the most direct empirical problems are related to the all-or-none fashion by which the defining features of the two processing modes are supposed to hang together. Factually, these features appear relatively independent and may co-occur in just about any combination (Bargh, 1989, 1992). Automaticity seems a relative matter. It can develop gradually with practice and it has been demonstrated that attributes related to speed and interference are context dependent—that is, determined by the novelty of the other subtask or to be ignored distractors (Cohen, Servan-Schreiber, and McClelland, 1992; MacLeod and Dunbar, 1988).

3.3 Limited capacity

The limited-availability element in capacity theories easily leads to tautological explanations. Experimental findings of limited capacity in attention performance are 'explained' by limited capacity in processing resources, while this latter kind of capacity limitation is inferred from the empirical fact of the former (see e.g., Kahneman, 1973; Crossley and Hiscock, 1992 for examples). Such reasoning is not better than 'explaining' the empirical fact that a potato-sorting machine can not sort more than 40 sacks of potatoes per hour *because* 40 sacks of potatoes is its maximal sorting capacity. This is a classical *circulus viciosus*—that is, what has to be explained (limited output capacity) is part of the explanatory construct (limited input[1] capacity).

Postulation of *multiple* processing capacities or a central controller or processor with limited capacity only leads to a restatement of the problem—i.e., 'why are these postulated subsystems limited?'. Evidently, these kinds of answers offer little insight into the problems associated with limited capacity (e.g., Allport, 1980b, 1989, in press; Neisser, 1976).

In opposition to these kinds of pseudo-explanations, several theorists (Allport, 1989, in press; Neisser, 1976; Neumann, 1978, 1987) argue therefore, that we should attempt to give a more concrete answer to the question why capacity is limited and what are the factors that determine the degree of performance decrements in multiple-task situations. This will be the major topic of Chapter 4 (particularly § 4.2.2).

3.4 Fixed capacity

Another major problem of capacity theories is that they not only presuppose attentional capacity as limited but also assume that this quantity of available input is *fixed*. Input

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[1] In resource theories, input is used in a rather unusual sense, i.e., it does not refer to external information but to the internal faculties (reservoirs of 'fuel' or 'energy'), allowing the subject to process this information.

capacity is assumed flexible in a rather trivial way, i.e., with regard to the amount of effort (in relation to arousal, fatigue or intentions) invested and the way it is distributed over subtasks in proportion to subtask difficulty or demand (e.g. Kahneman, 1973; Wickens, 1992). In general, subjects are assumed to dedicate their full amount of resources to task performance. Therefore, unless intentionally varied, the total of available resource input is assumed to be allocated in task performance and the upper limit of this available quantity is assumed to be fixed (Gopher and Sanders, 1984).

Especially with reference to resource theories, it is rather puzzling how distinctions between skilled (trained) and unskilled subjects could be introduced into a processing theory assuming fixed available capacities. Because resource theories are based on the conception of the subject as a physical system, again the potato-sorting machine may be used to illustrate this conceptual problem[2]. When, after a technical innovation in such a machine, the number of sacks of potatoes that can be sorted in a period of time appears to be increased, it sounds rather far-fetched to conclude: 'true the machine has been improved in some respects but its capacity still is the same'. If one wants to defend this reasoning, at least this assumption should be specified in terms of a metric defining this capacity. If this is not possible, and capacity remains to be used as a global concept, one will have to provide good reasons for keeping fixed-capacity thinking upright. Otherwise, it is more credible to conclude that the improvements have changed an underlying mechanism, causally related to global capacity.

In this connection, the general solution is to explain training-related performance variations with fixed capacity by a more *efficient* use of limited resources, particularly by automatic processing (see § 2.4). According to dual-process theory, training under consistent mapping conditions leads to highly efficient processing and thereby to capacity-independent task performance. For this reason, resource theories and dual-process theory may be regarded as complementary. That is, resource theories deal with interference in various multiple-task combinations or difficulties, and dual-process notions capture effects of practice on single- and multiple-task performance.

3.4.1 Automaticity reconsidered

Because the concept of automaticity is usually invoked to explain training effects with fixed available input, some basic problems and limitations with regard to dual-process theory need to be explicated.

As was stated in the previous chapter, automatic processing is: fast, parallel, effortless, independent of attention, not under direct subject control, does not suffer from or cause

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[2] Since this thesis concerns human-beings, my partiality to potato-sorting machines may sound a bit curious, but is should be considered a major step forwards in comparison to the copper wire of Broadbent (1958) as the metaphorical basis for resource theory.

interference, is not limited by short-term memory capacity, and does not necessarily give rise to conscious awareness (pre- or postattentive).

Characteristics

First, these characteristics are not generally accepted. Particularly the criteria related to interference, subject control, or intentionality, and the all-or-none status of attention and automaticity may be abandoned or treated differently (e.g., Bargh, 1992; Cohen et al., 1992; Neumann, 1984; Logan, 1992). It is for example difficult to see how automatic processes *do not suffer from, or cause, interference*, i.e., do not affect or are not affected by other task processes. When automaticity is conceived as a physical process, it can by definition interact with other physical processes. Therefore, on a basic level one may argue that, interference-free task performance is a metaphysical criterion falling outside the scope of (physical) science. Also, the idea that automatic processes are *independent of attention* seems not very likely. According to Cohen et al. (1992), only with the allocation of attention can a process—even if it relies on very well-learned skill—be carried to completion. Logan (1988, 1992) argues that automaticity must be defined in some other way than independence of attention because many forms of automaticity are dependent on attention ('postattentive processing').

Fixed capacity

The concept of automaticity does *not* substantiate that input capacities or resources are fixed. That a skilled task can be performed quickly, subconsciously, with minimal effort, without interference etc., may of course as easily be captured by the development of new, more independent, or increasing capacities as by constant capacity with reduced demands for capacity. Moreover, the results of studies showing limited transfer of single-task training to dual-task performance (e.g., Schneider and Fisk, 1984) are not compatible with explanations that solely depend on automaticity development. There seems to be more at stake. What thus may be concluded is that the dual-process notion is compatible with some skill-acquisition aspects of multiple-task performance in an overall fixed-capacity framework.

Underlying mechanisms

Although the dual-process theory may provide a potential explanation for training effects in a fixed-capacity framework, a major problem is the theoretical superficiality of this explanation. The theory in its most widespread form does hardly specify concrete *mechanisms* explaining how capacity becomes more efficiently used with training, despite the rather elaborate global descriptions of automatic and controlled processing. The

transition from subject-governed controlled to stimulus-driven automatic processing with extended practice is mostly treated as a kind of miracle. Evidence from other adjacent scientific domains—on the basis of EEG, PET, or CT studies—is rather meager. Given the rather metaphysical conception of automaticity as a capacity-independent process, the theory certainly is in need of data pointing at basic mechanisms embodying the supposed distinct processing modes. For example, studies based on evoked potentials (EEG) suggest that conscious information processing is strongly related to the nonspecific association zones of the cerebral cortex (e.g., Goff, 1969; Thompson and Bettinger, 1970; Vaughan and Ritter, 1970). At present, most proponents of the theory seem not to be able to substantiate the theory with such neurophysiological and neuroanatomical evidence.

Fortunately, in some recent papers, the lack of an explicit description of the kinds of learning that underly automaticity is acknowledged (e.g., Logan, 1988, 1990, 1992; Schneider, 1985; Schneider and Detweiler, 1988). According to these authors, controlled performance is based on attending to the various steps of the general algorithm executed to produce a solution, whereas automatic performance is based on single-step direct-access retrieval of past solutions from memory (Logan, 1992). Hence, automaticity is regarded as a memory phenomenon. Logan (1992) assumes that automatic processing is intricately dependent on attention, because memory retrieval depends on how a subject attends to the stimulus—an argument similar to that of Cohen et al. (1992). Likewise, Neumann (1984) has argued that automatic processing is not independent of a person's current intentions, i.e., the total task situation. Therefore, Logan (1988, 1990) conceives automaticity as *post*attentive rather than *pre*attentive. Indeed, the postattentive character of automaticity is rather inescapable with regard to motor routines.

Schneider (1985), Schneider and Detweiler (1988), and Detweiler and Schneider (1991) provide a quasi-neural model for changes in processing associated with skill development. In this model—which relies partly on communication theory— information processing involves transmission of messages between visual, lexical, semantic, and motor units. Automaticity is conceived the result of two kinds of learning: *association learning* and *priority learning*. Association learning is a mechanism by which one input message is associatively translated to another output message that can be transmitted for additional processing. Priority learning is the mechanism by which a processing unit determines the power with which a message is transmitted.

In opposition to the (preattentive) priority learning mechanism, Logan (1988, 1992) proposed (postattentive) *instance learning*. When attention is paid to an encountered object or event, obligatory encoding (building memory strength), obligatory retrieval (making past learning available for present problems), and instance representation (each encounter is encoded, stored and retrieved separately) will occur. This results in increasing availability of learned information with the number of attentional encounters. Instance theory claims that performance is automatic when it is based on the retrieval

of previous events from memory, rather than from a general algorithm. So far, this theory may be acceptable. However, Logan assumes that the decision to rely on memory is based on a race between independent memory traces and the algorithm. Each memory trace is assumed to be stored and retrieved separately. When, with practice, more traces enter the race, memory is more likely to win (Logan, 1988, 1990).

In the next chapter, I will show that brain functioning, i.e., the way neural circuitry is altered by experience (long-term memory), is incompatible with this rat race principle involving independent memory traces. In contrast, in § 4.2 and § 4.3, I will argue that higher organisms derive their amazing learning and processing power from their potentials to capitalize on relationships among neuronal processes (i.e., correlations, coincidences, covariances, combinations) allowed by their flexible, smart, and associative organization. In § 4.5, an alternative framework for learning mechanisms underlying skilled task performance will be provided. This framework not only builds on present psychological data, but elaborately incorporates current neurobiological knowledge as well.

'Ghost-in-the-machine' explanations

The variety of criteria for automaticity and the vagueness of the distinction with controlled processing makes it difficult to test this hypothesis (Hirst et al., 1980). When Shiffrin and Schneider (1977) state that controlled processes are *'activated under control of, and through attention of, the subject'* (p. 156), Allport (1980b) asks himself what this may mean. Does 'the subject' refer to the whole organism, implying that all processes within the system (including the automatic ones) are controlled? Or is 'the subject' equivalent to some sub-system, a central executive or ghost-in-the-machine? The first alternative is contradictory, the second displaces the problem, which leads to a *regressio ad infinitum*, i.e., who or what controls this central controller? The same kinds of questions regarding the status of the subject may be posed when automatic processes are supposed to be *'activated without the necessity of active control by the subject'* (p. 155/156). Are automatic processes activated under control of something that is not the subject or are they activated under passive control by the subject or without control by the subject? Again, what is meant by 'the subject' and what is the 'control' by this subject? The consistent high quality of performance in skilled tasks clearly contradicts the idea that automatic processing is 'lacking control'. Skills, such as walking, music playing, driving, reading, and typing are highly controlled in the sense that one must intend to engage in any of the automatic activities and one can stop them whenever one wants (Logan and Cowan, 1984). The presumed lack of control (autonomous, stimulus-driven processes) typically is referred to when automatic processes have to be modified, suppressed, or interrupted (e.g., Rogers and Fisk, 1991). Such modifications require the development or operation of processing routines or skills that are similar to the existing automatic

routines. Consequently, these phenomena merely may demonstrate the basic difficulty for the nervous system to keep similar, or related, operations distinct or separate (see § 4.3). Accordingly, control problems basically refer to control *beyond* the automatic process itself. When a task provokes well-learned automatic routines which disturb the performance of that task (e.g., a Stroop task) obviously the control *over* these routines is troublesome. It is therefore the control process itself that needs scientific clarification, that is: the development, programming, execution and monitoring of the mysterious highly efficient processing routines (seemingly capacity-independent) and the way such processes take place when these routines have not been developed or cannot be developed. Each model that does not explain *the subject's control process itself*, logically leads to homunculus explanations. Unfortunately, most authors even don't mention these kinds of fundamental problems with the theory, and it is therefore not very surprising that major advocates of the theory, such as Shiffrin and Schneider (1977), take little pains to provide clarification.

In general, psychological theories which are built on unexplained limited-capacity general-purpose central controllers (i.e., 'central processors', 'executives', 'supervisors', 'coordinators') often turn out to be disguised Cartesian ghost-in-the-machine proposals. When central controllers—or conscious subject-governed processes—are used as explanatory concepts in psychology, they should have a satisfactory theoretical base. As will be argued in Chapter 4, in biological systems, behavioral control is organized in such a manner that homunculi, i.e., mysterious controllers, are unnecessary (see Allport, 1980a, 1989; Van de Grind, 1984; Kilmer, McCulloch, and Blum, 1969; Neisser, 1976; Shallice, 1972).

Conclusion

After a thorough analysis of automaticity, Neumann (1984) concludes that automatic processing should be conceived as being controlled, but at levels below that of conscious awareness. The dual-process distinction seems thus a reformulation of the old thought (James, 1890) that in some cases tasks require much conscious attention whereas in other cases they do not. This rather trivial conclusion does not mean that the dual-process conception is a waste of theoretical effort and that it should be abandoned (as is for example propagated by Neisser, 1976 and Hirst et al., 1980). It merely should be conceived a first classification of a wealth of empirical behavioral data, and thereby a significant step in theory formation.

However, dual-process theory has not provided much insight into the problem of skill acquisition with fixed limited resources. Like multiple-resources theories, this theory starts with the unspecified assumption that capacity is fixed. Until very recently, it has thereby provided a spurious reason to divert from inquiries into the basic mechanisms related to the impressing capabilities of people to control their behavior in relation to

task demands and to learn from practice. This still leaves us with the (great and) really interesting questions regarding the basic mechanisms that cause limitations in multiple-task performance in different task combinations and training situations.

3.4.2 Time-sharing skills

The acquisition of unique time-sharing skills is conjectured as the development of more *efficient* processes, which are specific for dual tasks. This may explain the results of studies, showing limited transfer of single-task training to dual-task performance (e.g., Schneider and fisk, 1984). However, by presuming the development of efficient dual-task skills the deeper question is raised by what underlying processes time-sharing efficiency may be developed with equal initial capacity. The experiments indicating unique time-sharing skills, discussed in § 2.5, do not provide much knowledge concerning the nature of these skills. One important clue in this respect is that these skills are rather specific for the dual-task combinations involved. This means that dual tasks entail some general characteristics that do not exist in single-tasks, but that dual-task performance requires subjects to capitalize on the peculiarities of the *combination* of subtasks as well. A characterization of the nature of efficient dual-task skills, asks for an analysis of the information processing requirements of dual tasks in general and in specific dual-task combinations.

3.5 Neurobiology

Another weakness of capacity theories is that the notion that all tasks have to tap from one, or a limited number of, static energetic pools is strikingly independent of existing neurobiological knowledge. The brain does not work like a general purpose computer that always has to use one central processor, whether or not assisted by a limited number of more specialized co-processors. Based on the manifold methodologies (EEG, PET, CAT, and lesion studies), the literature documents a clear relationship between specific structural mechanisms ('resources' 'inputs', or 'processing faculties') and their functional properties. The degree of structural and neurochemical specificity of brain mechanisms, however, is much higher than has been hitherto acknowledged by e.g., multiple-resources theorists. For visual functioning, for example, separate mechanisms have been identified for dynamic form, color and form-with-color, and motion (e.g., Zeki, 1992). With respect to the mechanisms of attention, Posner and Petersen (1990) give a review of evidence pointing at a network of distinct anatomical brain areas involved in three kinds of visual-spatial attention: disengagement from the present focus of attention, shift of attention, and re-engagement on the new target. According to Posner (1990), these attention systems have their own identity, just like sensory and motor systems. Likewise, Carr

(1992) argues that the degree of selective involvement of different attention mechanisms in the brain depends of the task and past processing activity. In general, attentional processes do not have an all-or-none character and are, depending on the task, distributed over different structural mechanisms, serving many different functions. In a critical review of 25 years of attention research, Allport (in press, p.32-33 of a draft) concludes that the penalty for believing in 'attention' as a unitary (simple) construct is to be condemned to *'ill-defined (or even completely undefined) causal mechanisms and constraints— 'attention', 'attentional resources', central processing system, 'central executive', further processing', and the like—whose explanatory horse-power is nil.'* Therefore, traditional issues—like the identification of processes which do, or do not, require attention or localizing the bottleneck separating 'preattentive' from 'attentive' processes—need to be set aside. Instead, a more intricately articulated conceptual framework, linking cognitive and neurobiological processes at many different levels of description has to be adopted (Allport, in press). Some steps in this direction have already been made. Posner, Sandson, Dhawan, and Shulman (1989) have demonstrated that interference effects match very well with the architecture of underlying structural brain mechanisms as reflected by PET scanning. Interference between an auditory attention task and three common visual attention tasks, visual spatial orienting, semantic priming, and word form cuing, could be predicted on the basis of the overlap of anatomical systems activated by these tasks. This, and other relevant evidence for the high degree of specialization in brain mechanisms performing operations that also have been identified in behavioral terms, has been reviewed elsewhere and will be partly recapitulated in § 4.2.3.

In addition, the fixed-capacity assumption of capacity theories is in disagreement with the well-known tendency of neuronal circuits to change as a result of activity. Action potentials not only transmit and encode information. in addition, their metabolic after-effects alter the circuits over which they are transmitted. This may involve changes in the function (efficacy, amount of transmitter release, numbers of receptors) and the number or location of synapses. Axons sprout new endings when their neighbors become silent, and the terminal branches of dendritic arbors are constantly remodeled. Synaptic contacts between synchronously active pre- and postsynaptic neurones are selectively reinforced and synaptic contacts between asynchronously active pre- and postsynaptic neurones are selectively eliminated (Cline and Constantine-Paton, 1991). These processes are considered the basis of the so-called Hebb doctrine stating that individual cells can, by being activated at the same time, come to form cell assemblies, which may make up the structural embodiment of memory and learning phenomena (Hebb, 1949). Given the absence of a reasonable measure for input capacity, the high degree of neuronal plasticity makes the fixed capacity assumption quite speculative and unlikely.

In other words, just as is the case with our sensory and motor organs, such as eyes, ears, hands and feet, underlying structural inputs and behavioral capacities evidently are

related with high degree of distinctiveness. When people are conceived to have different information processing capacities with resource functions, this knowledge should not be neglected. Furthermore, when people are trained in physical sports, such as the marathon or weight lifting, nobody would claim that such activities do not affect their capacities of, say muscle strength or blood circulation system. It would be untenable to start with the assumption that enhanced physical performance is just a matter of efficiency.

Given the wealth of relevant data, one provoking question will linger throughout this manuscript: why are biophysical entities such as our possession of specific muscles and joints, two eyes, two ears and two hands and of one mouth, so easily and fruitfully coupled with their functional properties in behavioral sciences (e.g., 'structural interference', Kahneman, 1973), but the fact that we have a structurally differentiated and plastic brain not? Form and content cannot exist independently of one another. Similarly, structure and function are intrinsically coupled, and should therefore be approached as such.

Some attempts have been made to bring resource conceptions in accordance with the characteristics of neuronal information processing (Detweiler and Schneider, 1991; Schneider and Detweiler, 1985; Schneider and Detweiler, 1988) or with the structural and functional specialization of brain zones (e.g., Kinsbourne and Hicks, 1978; Polson and Friedman, 1988). Schneider and Detweiler (1988) provide an interesting connectionistic model for skill development in both single- and dual-task processing. This model provides a mechanistic explanation for the development of automatic processing and mechanisms concerning the development of specific dual-task skills as well. This model is feasible on a neuronal level, but is not completely in line with our present knowledge of the brain. The model still uses a central control system modulating the transmission of information and does not incorporate the selective formation (and degradation) of neuronal circuits with learning. In addition, the emphasis of this connectionistic model on message *transmission* suggests that information *processing* itself is left unexplained. For example, Schneider (1985) assumes that '*processing is done by the transmission of messages between specialized processing units*' (p. 477). In the next chapter, when training effects are discussed, I will provide a more elaborate discussion of the strong and weak points of this framework. In general, the rather crude framework of processing faculties with fixed processing capacities, as proposed by resource theories, is not in harmony with a huge amount of elementary neurophysiological, neuroanatomical, and neuropsychological knowledge.

3.6 Discussion and conclusions

This chapter presented some objections against the fundamentals of capacity theories as an explanatory framework for human performance limitations in multiple-task situations. These objections also concerned the monolithic and pseudo-explanatory concept of attention as used in dual-process theory, which is largely complementary to resource conceptions. In general, the conceptual basis of these current frameworks lacks explanatory power and does not account for behavioral plasticity with training.

Of course, this may be defended by considering the resource concept as a hypothetical intervening variable—a heuristic concept imposing conceptual organization of phenomena in the field. For instance, when studying task performance of a skilled operator in relation to different task environments in process industry, fixed capacity may be regarded as an adequate heuristic[3]. The same applies for the behavior of untrained subjects, participating in laboratory experiments involving simple perceptuo-motor or cognitive tasks. However, with respect to complex (professional or everyday) tasks, in which training and experience play a substantial role, or topics involving performance alterations with increasing age, the limited-capacity and fixed-capacity notions do not provide any insight into the dynamics of underlying mechanisms determining multiple-task performance. The resource concept has generated labels, rather than explanations. Furthermore, scientific knowledge should be accumulating. This means that explanations should link both with our knowledge of human behavior as being capable of dramatic improvements and with our knowledge of the brain as a flexible and intricate network. When the system itself clearly is not fixed, why then postulating that its capacity should be fixed, without providing a metric for capacity?

When attentional capacities are conceived as flexible and highly differentiated, explanations referring to variable efficiency input is used with, are insufficient. In that case, the localization of efficiently (automatic) performed processes outside the subject—which is very similar to the everyday meaning of the term automatic—while keeping controlled processing under control of the subject, can easily be unmasked as an old Cartesian homunculus 'explanation', leaving the control process that determines capacity unexplained. In other words: for well-trained tasks, the control problem is literally explained away, and for untrained tasks, a mysterious central controller is invoked, such that the control problem can be disregarded. The main function of a central controller would be to maintain a coherent and goal-directed pattern of actions (e.g., Allport, 1989). In order to be able to do so in a controlled task, a central controller would have to select and contain all relevant control parameters concerning the involved lower systems, such that it can take the proper decisions. Furthermore, it would need a

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[3] Knowles (1963) for example, analyzed workload of well-trained process operators, for which a fixed-resource conception may be a satisfying first approach.

very high afferent and efferent channel capacity in order to be able to receive and (re)distribute action and control parameters. If a central controller would exist, these kinds of properties still deserve a scientific explanation. Moreover, such a central command system—which would have a very prominent place in the total architecture of the nervous system—has never been identified. It must be clear that invoking a central controller merely displaces the problem of action control.

In conclusion, it is difficult to see how theories of human performance referring to *one type of (central) attentional input* with a *fixed capacity* that *is, or is not, required* in task performance could have any well-defined meaning and explanatory power. As Navon (1984) has pointed out, resource conceptions may turn out to be 'excess baggage', like a soupstone. Take the stone out of the soup, and the soup is still as good as it was. As I have tried to make clear, this soupstone metaphor still is rather weak. People like to eat their soup without stones in it. Excess baggage not only is redundant, but may also turn out to be a serious burden. Providing pseudo-explanations for the significant problems will divert interest from these problems, which may ultimately hamper scientific progress.

When a conception of a dynamic and structurally and functionally differentiated information processing network is adopted, processes such as multiple-task performance, selective attention, learning, maturation, or aging may be explained in one unifying theoretical framework instead of by an incoherent abundance of paradigm-specific mini-theories. The following kinds questions may then be answered. What underlying mechanisms determine variations in processing capacity with training or with aging? How do people manage to behave purposively and coherently, without monolithical attentional controllers in their heads? What makes up the skills allowing for information processing being so efficient and/or powerful in complex everyday tasks? What is the nature of abstract knowledge and how are psychomotor skills developed and preserved, i.e., what is the nature of 'memory' and how does it work? The answering of such questions within a unifying framework of performance theory may lead to a genuine accumulation of applicable knowledge.

In the next chapter, knowledge relevant to these kinds of questions will be reviewed. Some new (and old) ideas will be introduced, which may form the basis of a true explanation of the control process in biological information processing.

Chapter 4

A cognitive neuroscience framework for multiple-task performance

4.1 Introduction

There is an abundance of empirical data concerning attentional limitations and, if you use your fantasy, there are various conceptual frameworks conceivable that may capture most of them. However, in order to place constraints on theory formation and to construct theories that entail *accumulating* knowledge, one powerful principle can be advocated: the theory should be compatible with our knowledge of the basic characteristics of the system used for biological information processing... the brain. Psychological phenomena are natural, emerging from the physical brain—i.e., the mind is what the brain does (Kosslyn and Koenig, 1992). Accordingly, current knowledge concerning the brain determines what can be considered a legitimate psychological conception and what can be rejected at forehand. Because major advances in science often consist in discovering how macroscale phenomena relate to their microscale constituents, behavioral neurobiology provides valuable starting points for psychological theory formation (Churchland and Sejnowski, 1992).

Therefore, the present chapter starts with an overview of the basic aspects of brain functioning and organization as far as these are relevant for attentional tasks. Afterwards, the nature of attentional limitations and data concerning factors affecting attentional performance will be discussed. Finally, a theoretical framework will be presented that is compatible with general neurobiological as well as psychological data. Not all ideas presented in this chapter will be devoid of some speculation. Of course, such an approach entails the risk of being attacked by theorists who are afraid of synthesizing knowledge over different levels of aggregation. However, since modern psychological science recurrently is depicted as disorganized generation of data (an 'exploding confetti factory'), each endeavor to organize significant segments of these data into a consistent overall framework must be worth the risk of such criticism.

With respect to the to be discussed data and notions concerning multiple-task performance, I will not go into the peripheral bio-mechanical problems associated with some dual-task combinations. On the perceptual side, the eye cannot simultaneously focus on two separated locations and stimuli for one task may be masked by the concurrent stimuli of another task. Likewise, on the motor side, tasks may require people to execute physically incompatible actions, such as talking and singing, drawing and

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catching a ball with the same hand, or type-writing and piano playing with the same hands. These kinds of rather trivial phenomena will not be considered.

People can also perform dual-tasks by *shifting* attention and performance between subtasks. In that case, they actually do not engage in time-sharing, rather they are alternatingly directing their attention to one task and to the other. The present thesis is devoted to possible underlying neurobiological and psychological mechanisms enabling subjects to do things simultaneously, thereby treating attention as a construct that has to be explained rather than as an explanatory construct. Therefore, processes like shifting of attention in multiple-task performance will not be distinctly considered.

4.2 The brain

4.2.1 Basic mechanisms

Organized interconnectivity

The human brain is sometimes honored as the most complex object known in the universe. Packed into a volume of about 1.5 liters, it comprises 10^{12} (trillion) cells, 10^{11} of them neurons linked in networks by about 10^5 km of wiring and 10^{14} or more synaptic connections. In addition to neurons, conceived as the primary elements of information processing, the supportive glial cells regulate local levels of extracellular ionic concentrations and other substances (included neurotransmitters), thereby modulating graded potentials and action potentials (Dowling, 1987; Moonen et al., 1990). With that, the interaction complexity of the nervous system goes far beyond our imagination.

This complexity, however, is not without order. The cortex shows a heterarchical and distributed organization, consisting of two kinds of narrow columns of regularly connected neurons, i.e., mini-columns (Mountcastle, 1978) and macro-columns (Szentagothai, 1975). Supposedly in order to economize on wire, columns contains neurons with some similar specificity. For the visual cortex, such stimulus specificities may be: wavelength, ocular dominance, preferred disparity, preferred position in oculocentric visual space, preferred orientation, or preferred direction of movement. For example, based on experiments in which the fourth visual area was penetrated with micro-electrodes, Zeki (1980) found narrow-band cells with particular color preferences, orderly grouped in clusters perpendicularly oriented relative to the cortex. Generally each individual cell belongs to a number of columns and its stimulus specificities are defined by its columnar allegiances.

In the brain, not everything is connected to everything else. Cortical neurons are rather sparsely connected relative to the population of neurons in a cell's neighborhood, i.e., to about 3% of the neurons in the surrounding square millimeter of cortex (Stevens,

1989). The neurons within cortical columns receive input from common afferent fibers and send their output by some hundreds of pyramidal cells with inhibitory connections with adjacent columns (e.g., Eccles, 1977; Szentagothai, 1975). Forward projections to one area are generally matched by recurrent projections back to the area of origin (Churchland and Sejnowski, 1992). At least in the visual cortex, long-ranging tangentially oriented axon collaterals of pyramidal cells interconnect discrete clusters of cells with similar functional properties (e.g., Löwel and Singer, 1992). These tangential connections probably contribute to scene segmentation and figure-ground segregation on the basis of the detection of relatively *global* characteristics of the information, such as spatial continuity of contours, similarity in orientation, or coherence in stimulus motion (e.g., Engel, König, Kreiter, and Singer, 1991).

The brain is remarkably efficient in power consumption. The energy consumption of a neuron per operation (one synaptic activation requiring 10^{-15} joules of energy) is a factor 10^{-8} of the energy required by the most efficient silicon technology per operation (multiply, add, etc.). A direct consequence of this efficiency is that even the modest brain of a resting fly can perform the same number of operations per second as about 100 of the newest supercomputers collectively (Churchland and Sejnowski, 1992).

Plasticity and learning

Although the brain does not have unlimited capacity to accommodate to damage, it is really a highly flexible, adaptive, and self-organizing system, continuously updating and tuning itself to the information provided by the environment. Virtually all of a brain's functions, including perception, motor control, thermoregulation, and reasoning, are modifiable by experience, but the degree of plasticity may vary considerably—that is, from a malleable domain of fast-and-easy changes to a more permanent but still deformable domain of 'semi constancies' forming a kind of 'unity-of-self' through time (Churchland and Sejnowski, 1992).

The heart of the explanation of learning is to explain global changes in the brain's output on the basis of orderly local changes in individual cells. The changes in behavior from which one infers functions like learning and memory depend upon structural modifications primary caused by action potentials. Action potentials alter the function, the number, the anatomy, and locations of synapses of the circuits over which they are transmitted. All aspects of these modifications have impact on the connectivity in the brain, and thereby its circuitry. Based on environmental stimulation, the fine architecture of this circuitry can change dramatically in a very precise and selective manner (e.g., Hirsch and Spinelli, 1970; Blakemore and Cooper, 1970). Alterations may involve selective reinforcement and formation and selective weakening and dying of connections and response properties of cells. The essence of Hebb's (1949) insight concerning neuronal plasticity and learning was that spatial contiguity and temporal relations are

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crucial determinants of the selective modifications of connectivity. Functional similarities, take the form of *coincident* or *coherent* activity patterns, i.e., coactivation of cells, whereas cells responding to different feature constellations in a scene are uncorrelated (e.g., Engel et al., 1991; Engel, König, and Singer, 1991).

In general, synaptic contacts between synchronously active pre- and postsynaptic neurones are reinforced and synaptic contacts between asynchronously active pre- and postsynaptic neurones are degraded (Cline and Constantine-Paton, 1991). On the basis of these associative changes in synaptic strength, individual cells can form cell assemblies that make up the structure in which e.g. 'memory' is housed. Neurons wire together if they fire together (e.g., Changeux and Dachin, 1976; Hebb, 1949; Löwel and Singer, 1992; Stent, 1973). This process allows for associated (world) events (i.e., invariance and covariance, Gibson, 1966, 1979) to be represented by cell interaction. It gives a basic answer to 'where does knowledge come from?' Like Darwin's answer to 'where do the species come from?', according to this Hebbian principle, neuronal information processing is characterized by competitive interaction in which innate and environmental factors continually determine which connections and circuitry will survive and which will perish (e.g., Cronly-Dillon, 1991). In the kitten visual cortex, for instance, selectivity in horizontal connections is achieved by elimination of inappropriate connections, which is influenced by experience on the basis of correlations of activity in interconnected cells. This means that weakening of the connections between synapses should not automatically be identified with forgetting or decay of skills. Reduction in synaptic strength is an indispensable component of learning new invariants or, alternatively, a part of sloughing off the irrelevant. Cell death is one of the most remarkable facts about development (Oppenheim, 1985). In some structures, up to 75% of the founder cells die during maturation.

These simple facts concerning the fundamental principles of learning imply that theories which treat the human information processing system as static and incapable of modification of its structural input capacity (see Chapter 2 and 3) should be treated with caution when it comes to an adequate understanding of human behavior.

Brain programs, skills, and knowledge

Unlike computers, structure and function in the brain are intrinsically coupled. This means that concepts such as content-independent or material-independent programs, processors, and stores are inadequate concepts for the description of human performance. According to Van de Grind (1984) these concepts are unbiological abstractions related to the so-called *computer fallacy*. The computer fallacy is based on the strict distinction between software and hardware. The program I use on my computer for writing the present manuscript can run on the computers of most of my colleagues. Also the information in the manuscript can be moved to other computers, floppy disks

or to other places on my harddisk, the memory of my computer. Adopting the 'silicon' information processing metaphor for neuronal information processing, has led to the erroneous idea that biological information processing involves relocatable programs or information (software) stored in memory and run in the processors (hardware) of the brain. In biological systems, however, such possibilities are quite absurd. In the brain, the function of a neuronal action sequence—say a specific pattern of axonal action potentials sent to adjacent neurons—is strictly determined by the properties of the neuronal configuration (structure) in which this neuron is embedded. In addition, neuronal activity alters the circuits that are involved in this activity. This is well-illustrated by the fact that memory, which was formerly conceived as a system consisting of a limited number of content-independent subsystems (e.g., semantic *vs* episodic), is being fractionated as a result of recent psychological and neurobiological studies. Numerous material-specific memory systems have been identified, such as memory for faces, objects, words, numbers, and so on (Desimone, 1992). Desimone (1992) refers to various studies that jointly point at 10 cerebral areas, with known non-mnemonic functions, that are involved in related memory functions (e.g., premotor cortex prestriate visual cortex, inferior temporal cortex, cerebellum, striatum). Accordingly, mnemonic contributions of a given brain structure are usually determined by its non-mnemonic functions. Furthermore, animal studies suggest various ways in which neuronal activity is altered when 'knowledge' is incorporated into the structure of the brain, e.g., tuning, adaptive filtering, sustained activation, and association (e.g., Desimone, 1992). Berlucchi and Buchtel (1975) describe several possible neuronal mechanisms that may be the basis for classical conditioning.

Therefore, in the brain, (fixed) hardware and (flexible) software are closely related. Together they make up the *wetware*, i.e., the *programs of the brain* (written in 'neuronese'). Brain programs, can be defined as neuronal control structures or networks modulating and redistributing incoming neuronal activation patterns and coding for a number of potential output or action sequences (parameter specification). Brain programs may handle parameters coming from other brain programs and give their output to brain programs, including the original brain programs. With this definition, brain programs are the local and structural analogues for the more global functional concepts of *knowledge* and *skills* (the control structures building long-term memory). This implies that also these latter psychological constructs should not be understood as relocatable information, 'stored' somewhere in the 'harddisk' of long-term memory. In other words: brain programs, embodying skills and knowledge do not 'use' capacity, or 'tap' resources, they *generate* capacity.

In general, the self-organizing nature of neuronal circuits means that memory and processor are one and the same thing (Nickerson, 1977). So we better may forget about content-independent processors, and material-independent supervisory mechanisms and memory systems. Apart from global task characteristics, task performance will be content-dependent, that is, determined by concrete patterns, configurations, and contexts

in which task elements are embedded (Allport, 1980a). Unlike a digital computer, which is general-purpose and can be programmed to run any algorithm, the brain appears to be an interconnected collection of special-purpose mechanisms that are very efficient in performing their tasks but limited in their capability to execute another function (Churchland and Sejnowski, 1992).

Smart and special-purpose mechanisms

Brain programs have a very efficient and purposive geometric organization, which develops during ontogenesis on the basis of coincident activity in connected cells. In interaction with the environment, neuronal wiring and connection weights (strength) become tuned at the complexities (invariant and covariant properties) among input processes, central processing operations, and output processes, such that elementary, time-consuming, calculations are unnecessary. Therefore, brain programs are called *smart* (Runeson, 1977; Runeson and Bingham, 1983; Van de Grind, 1988; Wagemans, 1990). This means that they execute a seemingly complex[1] feat without having to 'calculate' on the intermediate steps in which *we* conceptually analyze that achievement. They typically capitalize directly on the specific structure of the task (content-specific). Smart mechanisms are therefore also called *special-purpose* mechanisms. A nice example of an artificial smart mechanism is the polar planimeter, which directly calculates surfaces without processing linear measures. Biological examples are the bilocal movement detector (e.g., Van de Grind, Koenderink, and Van Doorn, 1986), the looming detector (e.g., Regan and Beverly, 1978), or the neurons found in the fourth visual area, concerned with color constancy (e.g., Zeki, 1980). Looming detectors, for example, can directly translate the rate of visual image expansion into an appropriate command (e.g., brake or catch). Looming detectors circumvent the problem of estimating distance and velocity in 3D and of calculating time-to-contact from these primitives, which may be perceptually very complex. Much of the high processing performance of the brain results from the continuous functional validation, adaptation and formation of smart, special-purpose, mechanisms. More elaborate descriptions of biological smart mechanisms can be found elsewhere (see Van de Grind, 1984, 1988; Wehner, 1981).

Albeit that brain programs are structured from a few basic components, combined in endless varieties, complex systems of these basic mechanisms cannot be studied sensibly at this detailed 'rote' level (Van de Grind, 1988). Likewise one must not try to predict the weather by calculating on the behavior and interactions of individual molecules.

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[1] In this connection, 'complex' refers to the scientist's point of view. What is conceptually complex for a human may be very simple to the smart mechanism. Therefore, our favorite introspective intuitions may be very misleading with regard to the nature of the computational problems the nervous system is solving and the difficulty of these problems (Churchland and Sejnowski, 1992).

Heterarchical organization

Brain programs are intricately distributed and heterarchically (or reciprocally) organized. Although hierarchical relationships between subsystems can be shown, particularly within sensory and motor areas (e.g., Felleman and Van Essen, 1991; Van Essen and Maunsell, 1983), the majority of evidence points to parallel processing and heterarchical control (Allport, 1989). According to Allport (1980a, 1989), the performance of the whole system depends on the co-operating contributions of many specialized subsystems. In the network of networks, no subsystem can be characterized as uniquely 'central'. This is even so for a system with many hierarchical components, such as the visual system. Experimentalists have not found one particular region in the brain where all the information needed for visual awareness appears to come together (Zeki, 1992). Furthermore, neuropsychological reports show that a system on top of the visual hierarchy and which receives inputs and projects to many parts of the brain, the hippocampal system, is not essential for visual awareness (Crick and Koch, 1992). Also on theoretical grounds it can be argued that such a theoretical "Cartesian Theater" does not exist (e.g., Dennett, 1991). However, as I will argue in § 4.2.2, a subsystem can be temporarily dominant, for instance, when it is facilitated by previous inputs such as task-instructions.

Behavior emerges from the multiple interactions within a system of components, rather than as the property of the individual components themselves. However, because massive interference would result when input/output mappings were established in the same component, the brain relies on the principle of division of labor (Kosslyn and Koenig, 1992). For visual object recognition and localization, for instance, separate and parallel systems have evolved (see § 4.2.3). Because neurons accomplishing similar functions use the same input and output channels and must interact quickly, such functional networks are typically localized. However, not all of a network needs to be localized to a given area of the brain (Kosslyn and Koenig, 1992). Furthermore, the same networks can be member of more than one processing subsystem. For example, neurons in visual area MT, which respond selectively to motion, are assumed to work with subsystems that distinguish shapes and with subsystems that track moving objects (Van Essen, 1985). Likewise, the primary motor cortex has been found to contain sensor and sensorimotor cells (Miller, Riehle and Requin, 1992). Just as a particular feature can be shared by many different patterns, a particular cell can be shared by many different representations. It participates at different times in different 'assemblies' of co-active neurons and several of such assemblies may coexist in the same network. The code is thus relational—the significance of an individual response depends entirely on the context set by the other members of the assembly. This is very efficient and flexible because individual cells can participate at different times in the representation of different objects (Singer, in press).

Finally, the function of a neuron or a brain program is determined by its role in the system. That is, the function of systems is the total set of input/output mappings, depending on its (changing) internal structure and the circuits that bring it information, which themselves play a particular role by virtue of their place in the relatively stable overall geometry of the brain. In § 4.2.3, I will discuss basic characteristics of this geometry.

4.2.2 From neural mechanisms to behavior control

Neural competition: basic mechanisms for behavioral coherence and limited capacity.

On the basis of the immense high degree of neuronal interconnectivity, information can be processed in a highly associative way. Associative information processing allows the system to detect coincidences, i.e., invariance and covariation on various levels, resulting in Hebb-like circuits. Despite the associative character of neuronal information processing, mature organisms appear to be capable to maintain a uniform course of action independent of other sources of information that specify alternative action control parameters. Active organisms always show *goal-directed behavior*. In order to ensure this goal-orientation, an associative information processing system should be capable of controlling the degree to which different activations spread, or negatively affect one another. According to Churchland and Sejnowski (1992), the control of the immense arrays of muscle cells so that the whole body moves in the right way is probably the most fundamental problem to solve for an evolving nervous system.

Of course, scientific knowledge is not served by ascribing this control to a supervising system, a homunculus containing, comparing, and deciding on all quantitative data concerning the lower mechanisms. In contrast, control should be explained by the basic characteristics of neuronal structure, function, and organization. Basically, most of the answer to the problem of perceptuomotor control resides in the way neurons interact, alter themselves on the basis of coincident activity, and connect up to form circuits. According to Shallice (1972, 1978), control is accomplished by *mutual blocking*, or *reciprocal inhibition* among neuronal systems or programs. The degree of lateral inhibition by an activated system increases with its level of activation. Hence, activations generally will dominate over weaker ones because their inhibitory effects are stronger. When conflicting actions, such as talking and eating or braking and pressing the gas pedal, are roughly equally induced, such mutual inhibitions will ensure the dominance of one operation over competing operations, much like a 'flip-flop' mechanism. Therefore, the universal high degree of unity of behavior at any moment (Bullock and Horridge, 1965) is ensured by the magnification of potential small differences in activity. This dominance principle can be shown to follow mathematically, given certain simple properties of neuronal information processing (Shallice, 1972).

From the study of sensory systems, mutual inhibition is well-known to enhance the image contrast in the visual sensory field (i.e., Mach bands) or to sharpen the frequency sensitivity of primary auditory neurons (e.g., Furman and Frishkopf, 1964; Hartline, Rattliff, and Miller, 1961). Hellige, Jonsson, and Michimata (1988) notice that increase in arousal in the hemisphere contralateral to a stimulus is typically accompanied by an inhibition of arousal in the ipsilateral hemisphere. This is mediated at least in part by reciprocal inhibitory connections through the brainstem commissures. In addition, animal studies suggest that unilateral stimulation produces opposite facilitation and inhibition of homotopic brain structures (Leviel, Chesselet, Glowinski, and Cheramy, 1981). This may explain performance decrements when the same visual stimulus is presented to both visual fields and when both hemispheres have competence to analyze the stimuli and generate the response (Hellige et al., 1988). A clear subjective example of mutual inhibitory control among competing processes can be seen with reversible figures, such as the Necker cube. When people try to modify their percepts of these figures, they can hold only one interpretation at a time. Capacity may be conceived as limited in these situations because ongoing processes inhibit other possible processes. Also binocular rivalry, when incompatible images are presented to the two eyes and the system is thrown into oscillations, may be explained by strong reciprocal inhibition in combination with adaptation. In normal circumstances, weak inhibitory couplings may result in stable fusion (Lehky, 1988). Furthermore, commissurotomy patients (i.e., patients who have received a sectioning of the corpus callosum for relief of epilepsy) may show conflicting activities such as attempting to put on an article of clothing with the right hand and pulling it of with the left (e.g., Smith and Akalaitis, 1942). When conflicting perceptual tasks are presented to the two visual fields, these split-brain patients may not experience the perceptual conflict. The well-known fact that patients suffering from a multi-personality syndrome usually adopt only one personality at a time can also be regarded as an example of the selective dominance of neural systems. As will be shown in the next section, blocking may also be difficult when stimuli trigger well-learned ('automatic') processes.

Mutual inhibition may be supposed to select and maintain the appropriate attentional engagement when different (sub)systems are activated. However, this segregation mechanism seems not to prevent all forms of *cross talk* or *overflow*. Inhibitory surroundings around the central focus of activation cannot be fully impermeable (Braitenberg, 1977; Kinsbourne, 1980). A behavioral example of incomplete segregation of neuronal activity is that one's eyes swivel left when engaging in spatial thinking. In an experiment with equiluminant moving stimuli, Cavanagh and Anstis (1991) found substantial 'leakage' from the color channels to the luminance channel. Similarly, in an comprehensive analysis of the primate visual system, Felleman and Van Essen (1991) emphasize that although the system shows considerable segregation of information flow, there is also substantial intermixing and cross talk between streams at successive levels

of processing. In addition, with respect to the motor system, Swinnen and Walter (1991) point at studies documenting mechanisms that may be responsible for overflow and cross-talk in simultaneous movements of the limbs. In general, we always tend to synchronize limb movements and it is mostly rather difficult to move our limbs independently. Furthermore, 'horizontal' connections, e.g., through the corpus callosum, have been found to synchronize the responses of spatially distributed neurons and may thereby generate functionally coherent cell assemblies (Engel, König, Kreiter, and Singer, 1991). This 'temporal coding' mechanism may permit the coactivation of two spatially superimposed cell assemblies in the same cortical region, without being confounded (Engel, König, and Singer, 1991; Kreiter and Singer, 1992). Moreover, oscillations in phase (around 35-75 Hz) of neural discharges in different brain areas which process the same stimulus, are supposed to serve to associate representations in different cortical areas concerning this stimulus (Crick and Koch, 1990, 1992).

The incompleteness of neuronal inhibition in combination with the high degree of associative interconnectivity, may serve two overall functions. First, up to its highest levels of information processing, neuronal overflow may facilitate coincidence detection and facilitate synchronous neuronal activity contributing to the formation of new brain programs (see § 4.3.1). Second, overflow may keep the organism more flexible, such that it may change its goals and action plans when new and unexpected inputs 'interfere' with a current activity pattern. Flexibility may be important to such a degree that also an *interrupt* mechanism is needed, which can inhibit, or overrule, ongoing actions. This should be a major function of neuronal adaptation (Lehky, 1988) and the *orienting reflex*, that enables the organism to respond to potentially important stimuli (Sokolov, 1963). Cross-talk may explain many of the specific interference effects, whereas, according to Neumann (1987), the interrupt mechanism can explain some of the unspecific interference effects, both discussed in the previous chapter.

In general, it seems likely that mutual inhibitory control as well as neuronal overflow or cross talk may determine capacity limitations in certain task situations.

Apart from blocking or reciprocal inhibition, there may be other mechanisms that ensure the selective dominance of action systems and prevent cross talk. For example, prevention or modulation of cross talk may also involve isolation of synaptic complexes and modulation of neuronal interactions by astroglial cells. At present, knowledge concerning the precise role of these (flexible) cells in information processing is rather meager. Furthermore, on a global level, the brain is organized in relatively distinct functional systems that may operate in parallel without interference (see § 4.2.3).

The development of selective attention

Now I have discussed the nature of goal-directed behavior in terms of selective neuronal dominance, the present section deals with the development and adaptation of this selection process. The selection of elements of simultaneously available perceptual inputs and action control on the basis of this selection is traditionally referred to as *selective attention* (e.g., Neumann, 1987). Selective attention refers to our ability to direct attention at various *levels* of information-organization and within these levels at specific informational *targets* itself, i.e., events, places, or objects. For example, when listening to a talking person, we may attend to the level of phonemes, words, sentences, or reasonings. At a specific level of information-organization, we may also select one particular part (target) of the input—e.g., an interesting vocal message among other messages. Rather surprisingly, in the literature, this differentiation of targets and levels is hardly made.

Selective attention results from the combination of primarily *external* factors, such as stimulus quality, intensity, or magnitude, and primarily *internal* factors, such as skills, intentions, or motivations (e.g., James, 1890). That an external attention-demanding stimulus diverts attention from other targets is naturally captured in terms of the previously described competitive interactions among neuronal units representing alternative objects of attention. This competition could be the reason that target detection is generally faster and more accurate when the target is presented alone rather that in the presence of other stimuli, or when the target is redundantly specified.

Neuronal competition is also fundamental to the internal factors of selective attention. Internal factors, such as intentions or expectations can be understood as selective response facilitations or inhibitions in competing neuronal assemblies. Previous practice is a crucial determinant of selective modulation of this neuronal competition and thereby of the extent to which we are able to attend to different levels or portions of the available information. A young child may not be able to process verbal information beyond the level of words or elementary sentences. Adults can also direct attention to these low levels of discourse, for example when a difficult, or unusual term is used, or when they are instructed to do this. However, on the basis of previously acquired conceptual and verbal skills, attending to the higher-order semantic message usually will dominate. Furthermore, well-trained subjects have been shown to be able to attend to cues that remain unnoticed or even cannot be perceived by inexperienced subjects (Gibson, 1969).

At the other hand, in particular cases well-trained skills may constrain our selective capabilities. For instance, in Stroop tasks (Stroop, 1935) response tendencies activated by the well-learned semantic content of color names interfere with the desired outcome of reporting ink-color. Apparently, the processing of visual color information cannot completely block the strong tendency of processing verbal color information, i.e., reading.

The tendency to read interferes with color naming and occasionally dominates performance, as is indicated by false reading responses. What is the basis of such selective skills that usually will enhance task performance, but in some situations can degrade it?

When neuronal information processing is conceived as a process of competitive interaction and struggle for neuronal survival, it may be conjectured that practice leads to the formation and stabilization of specific (new) brain programs at the cost of other potential brain programs. With training, the surviving brain programs will need increasingly lower levels of activation in order to dominate behavior. Also environmentally or internally induced motivations (task instructions, intentions, expectations) will result in selective prioritization of brain programs. In skilled task performance, selective neuronal dominance allows subjects to react solely to the task-relevant stimulus inputs, ignoring the rest. In unskilled task performance, subjects do not yet possess the appropriate dominant circuitry, such that neuronal competition takes more time and the outcome will be less predictable.

The development of selective attention skills by training may thus be conceived as a process by which the system learns to adapt its current brain programs to the critical task parameters by selectively altering neuronal activation thresholds. Single-unit recordings in monkeys engaged in spatially selective attentional tasks have demonstrated selective facilitation of neurons that respond to visual stimulation in the attended region (Robinson and Petersen, 1986). No evidence has been found for input *filtering*—the idea that such spatially selective enhancement effect works through a process of sensory responsiveness *attenuation* in the unattended locations (Allport, in press). Moreover, when visual attention is focussed on a given location in the visual field, lower-level oculomotor systems that control saccades to other potentially distracting stimuli show reduced responsiveness (e.g., Goldberg and Segraves, 1987). According to Allport (in press), spatial attentional engagement appears to suppress *actions*, rather than *perceptual* qualities.

By such selective prioritization of perceptual mechanisms and suppression of non selected action systems, the selected systems will require less activation in order to dominate over the irrelevant ones. With practice, this may initially be experienced as a slow, effortful, and conscious process. That is, the appropriate programs do not yet exist. But by enduring consistent and coincident activation (stimulation-operation-feedback loops), the relevant circuitry will become structurally dominant, requiring low activation levels in order to determine behavior. This circuitry will only be activated by very distinctive 'trigger' inputs, when a specific internally and/or externally induced facilitation has occurred. This prevents that this circuitry can be triggered by irrelevant inputs, or in inappropriate situations, thereby interfering with task processes for which they are not intended. This issue will be addressed in more detail in § 4.5.1. Two kinds of brain programs will then be introduced that may serve a mechanistic explanation for skill

development with training and phenomena related to the 'automatic' and 'controlled' processing phenomena, as discussed in the previous chapters.

Limited capacity and selective attention

Few would deny that attentional capacity is limited and it has intuitive appeal to assume that selective attention has developed to deal with this limitation. This notion, for instance, attracted many theorists involved in the endless either-or controversy over early versus late selection. However, there is no *a priori* reason to assume that selective attention phenomena derive from a fixed structural bottleneck in neuronal information processing (Allport, 1989, in press; Neumann, 1987). According to Neumann (1987), limited capacity is not the cause of selective attention but it is a *consequence* of it. Neumann points out that capacity is limited because our system continuously has to select what to do and how to do it. This *selection for action* (Allport, 1987, 1989) is required in order to ensure coherent control of action, that is, to avoid the behavioral chaos that would result from attempts to simultaneously perform all possible actions with only one body, equipped with a few effectors (Neumann, 1978; Shallice, 1972, 1978; Allport, 1989). Any goal-directed action requires the specification of a unique set of parameters for its execution, parameters that determine a particular action rather than any other (Allport, 1989; Neumann, 1987).

This is undoubtedly true with regard to overt actions, performed with our effectors. However, with regard to the *covert* operations, required by cognitive tasks, such as trying to follow two simultaneous conversations or to perform two arithmetic tasks, this 'behavioral chaos' conception clearly does not hold. Why should we get into behavioral chaos when we easily could perform mental calculations, evaluate a new psychological theory and read a book at the same time? Wouldn't it be very *practical* if we were capable of doing that? Here, it seems that the authors mentioned above *a priori* assume some limited capacity leading to chaotic and incoherent behavior.

It can also be argued that this selection problem concerning the limited availability of effectors is rather trivial. During ontogenesis (and fylogenesis) the structure of the nervous system develops such that such effector conflicts hardly will emerge as potential action alternatives. As was stated before, a great portion of learning involves the selective pruning of existing neuronal wiring. Therefore, neuronal circuits initiating effector conflicts simply will not survive, whereas neuronal circuits preventing conflicts will develop and survive. An example of structural preclusions for effector conflicts is reciprocal inhibition among opposed muscle fibers, i.e., the smart neuronal mechanism causing direct inhibition of a potentially conflicting action just by the performance of the intended action. Reciprocal inhibition can be considered, at least with regard to the motor level, a structural impossibility of the combination of certain actions. The organism does not have to spend energy in deciding whether or not to do these actions at once

because the nervous system has evolved such that the possibility simply does not arise. Similarly, a fish will not fly and most birds will not swim under water because they are not 'made' to behave this way.

Following the presently advocated cognitive neuroscience orientation, selective attention originates independently of any *a priori* limitation of (central) processing capacity. The core of selective attention and limited capacity should primarily be found in the requirements of *goal-directed* behavior in active organisms (Allport, 1989) in combination with the demands posed by changing and unpredictable environmental inputs during locomotion. In a rich natural environment, animals have many different tasks and goals. They continuously have to select, program, control and monitor their actions in order to achieve the specific goals that are a prerequisite to their biological mission, i.e., survival and reproduction. The subgoals that are a prerequisite to fulfill this mission often have to be achieved under severe time constraints. Because there may be no second chance, appropriate action should be taken immediately. Basically, the high degree of smart neuronal interconnectivity provides the necessary processing and learning power and behavioral flexibility in order to adapt rapidly to miscellaneous environmental conditions. However, this high degree of interconnectivity and the high potential of spreading activations within the system, may lead to continuous attentional shifts and thereby disorganized behavior. The associative way of information processing may cause the system to continually change goals, thereby disturbing a consistent and coherent behavioral pattern. Accordingly, the critical problem for any attentional system is how to satisfy two conflicting requirements: *the need for continuity and coherence, against the need for high processing power and flexibility*. In order to maintain the appropriate attentional engagement over time during the course of an activity, the system has to inhibit and block potential conflicting action sequences when a goal is set and the accessory actions are carried out. This inhibition primarily ensures a certain degree of consistency and goal-directedness in intentional behavior.

However, in some instances unexpected or new conditions may require the organism to change its goals, for example by sudden attacks of an enemy. In order to keep up a certain minimum level of behavioral flexibility, the system also needs some 'associative overflow' among operations, or even an interrupt mechanism (e.g., the *orienting reflex*, first comprehensively described by Sokolov, 1963), that occasionally overrules ongoing activity. This may allow an organism to change its goals and action plans when new and unexpected inputs interfere with a current activity pattern. In conclusion, it is not solely the scarcity of effectors that forms the basis of selective attention and capacity limitations in task performance. These attentional phenomena are a consequence of the way animals have resolved the problem of combining *processing power* and *flexibility* with *goal-directedness*—i.e., by a high degree of interconnectivity, overflow, and inhibition.

4.2.3 Structural and functional differentiation

Neuroanatomical differentiation

On a macroscopic level, the central nervous system shows a clear hierarchical organization: spinal cord, hindbrain, midbrain, diencephalon, basal ganglia, cerebral cortex (e.g., Brodal, 1981). Furthermore, the cerebral cortex shows lateralization, i.e., areas with a function that is not shared by the homotopic area of the contralateral hemisphere. This lateralization is progressive at higher levels of cortical hierarchy. The modality specific and topographically ordered primary motor units or sensory projection areas show less lateralization than the secondary association zones, which in turn have less lateralization than the (highest) tertiary zones with integrative and cognitive functions (e.g., Luria, 1973).
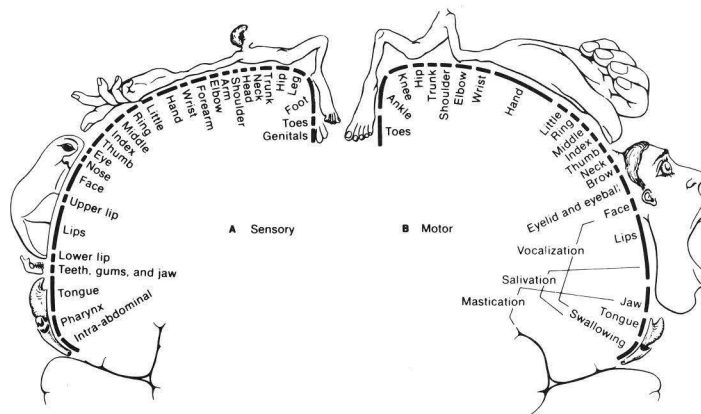
Fig. 4.1 (A) Map of a transverse section of the somatosensory cortex depicts the point localization of areas corresponding to their peripheral projections—that is, places in the periphery where the stimuli are subjectively 'felt'. Notice that the region representing the genitalia is tucked discreetly out of sight into the cerebral cleft. (B) Transverse section through the motor cortex, showing the projection of cortical regions to the skeletal musculature (Penfield and Rasmussen, 1950).

Globally, there is also a distinction between sensory (posterior) and motor areas (anterior). Within these two zones, discrete modality-specific primary and secondary areas are found, which in turn show a further differentiation (Fig. 4.1). In the cortex, for example, areas can be discerned for the high-level learned skill of visual word recognition in the left ventral occipital lobe (Petersen, Fox, Snyder, and Raichle, 1990),

color perception in the parastriate cortex (V4, Zeki, 1973, 1980), visual movement detection in the superior temporal sulcus (Dubner and Zeki, 1971), face recognition in the inferotemporal cortex (e.g., Young and Yamane, 1992), speech production in the lateral frontal lobe (Broca's area, e.g., Luria, 1973), or speech comprehension in the superior temporal sulcus. This organization of specialized areas is extremely complex. In the visual system of the rhesus monkey, for example, at least some 121 reciprocal pathways and 63 single pathways interconnect some 32 visual and visual association areas (Felleman and Van Essen, 1985). The visual system appears to be basically organized in a hierarchy 14 with levels, 10 of which cortical, with two *archicortical* nuclei at the top. Because of the high degree of reciprocal connectivity and the existence of various parallel channels, this hierarchy is not of a serial, feedforward kind. On a global level, two parallel visual systems are discerned. The most well-known example of parallel visual information processing in the visual system derives from the division between the parvocellular system and the magnocellular system. The parvocellular subdivision, which is selective for form and color, is concerned with 'what?', i.e., categoral identity. The magnocellular subdivision is concerned with 'where?', i.e., spatial relationships (from perspective, spatial organization, and figure-ground segregation). A behavioral dissociation between the parvocellular and the magnocellular system may be demonstrated with displays, which do not provide luminance-contrast information. For such *equiluminant* displays, the perception of distance and three-dimensional shape based on two-dimensional depth information can be severely degraded (Livingstone and Hubel, 1988).

Neuropsychological differentiation

Selective damage of parallel visual subsystems can produce striking symptoms. Mestre, Brouchon, Ceccaldi, and Poncet (1992) describe a stroke patient with bilateral cortical blindness with preserved visual associative areas, i.e., parts of V2 and V3 and V5. Although this man was unable to detect objects or large, highly luminant stimuli in the majority of the visual field, he was able to perceive optical flow motions in 'blind' parts of his visual field. He also could discriminate different velocities and directions of motion. It was concluded that the subject's ability to move freely in his environment was due to preservation of these 'blind' extrastriate visual pathways. Likewise, Weiskrantz, Warrington, Sanders, and Marshall (1974) reported about a subject who subjectively did not 'see' anything, though he was able to localize visual stimuli with remarkable accuracy. This phenomenon was called 'blindsight'.

Neuropsychological literature documents an astonishing variety of such behavioral phenomena, often demonstrating so called *double dissociations* (Teuber, 1959). A double dissociation appears when local brain injury selectively destroys one specialized sub-system or connection, impairing a circumscribed function (say musical performance)

leaving another function (say verbal comprehension) intact, whereas another injury only causes the inverted combination (e.g., disturbing verbal comprehension and sparing musical performance). As one of numerous examples, Luria (1973) describes the different effects of temporal damage as opposed to parieto-occipital damage. Temporal damage leads to disturbed acoustic analysis and affects any function which depends to any marked extent on this analysis and the greater the dependence, the greater the functional disturbance. Conversely, damage in the parieto-occipital zone, which is associated with spatial orientation, will spare all those functions dependent upon phonemic analysis but disrupt all functions which have a dependence on spatial orientation. Likewise, people with strokes suffer surprisingly specific visual losses; for example loss of color discrimination without impairment of form perception, loss of motion perception without loss of color or form perception, or loss of face recognition without loss of the ability to recognize most other categories of objects or loss of color or depth perception.

The abundance of reported double dissociations have strengthened the certainty of our knowledge concerning the relation between specific structural inputs and psychological functioning. Although it will be clear that the nervous system is a vast network of networks with various regions specializing for various tasks, single area's cannot be conceived as *the center* for a circumscribed capacity or function in the sense that its normal functioning is *necessary and sufficient* for its execution. Given the highly interactive nature of nervous systems, such a high degree of discrete localization may only be found in the simplest behaviors of the simplest animals (Churchland and Sejnowski, 1992).

Differentiation and dual-task performance

The relatively independent existence of different and parallel subsystems can be responsible for the fact that we sometimes can do two things at once. For instance, parallel visual subsystems such as the parvocellular, the magnocellular system or the tectopulvinar system may enable us to walk through a corridor while reading a book without noticeable difficulty. The aforementioned kinds of neuroanatomical and neuropsychological knowledge can be fruitfully utilized in the formulation of theoretical questions and in theory building. For example, according to the dichotomy of early versus late selection, selective operations on spatial/sensory properties of stimuli are attributed to (by definition) an early stage of processing and operations on categorical/semantic aspects are attributed (by definition) to a late stage of processing (Allport, 1989, 1983). This is difficult to reconcile with this data indicating functionally and neuroanatomically separable, parallel visual subsystems for these operations.

With respect to dual tasks, researchers have found evidence that two tasks can be performed without interfering with each other as long as the required information

processes involve different cortical structures (Hellige, Cox, and Litvac, 1978; Kinsbourne and Hicks, 1978). The general principle is that two operations performed simultaneously by the same or heavily interconnected structural systems will produce specific interference or interaction effects (e.g., Posner, Sandson, Dhawan, and Shulman, 1989). Thus in righthanders, vocalizing and right-hand performance mutually interfere more than vocalizing and left-hand performance (e.g., Kinsbourne and Hicks, 1978). This can be explained by the hemispheres underlying these tasks. On a more local level, it has been shown that interference effects match very well with the architecture of underlying structural brain mechanisms as reflected by PET scanning (Posner et al., 1989). The pattern of interference between an auditory attention task and three common visual attention tasks, i.e., visual spatial orienting, semantic priming, and word form cuing, could be predicted on the basis of knowledge concerning the anatomical systems activated by these tasks. Auditory shadowing (repeating back auditory words) shares the anterior midfrontal attention system with cuing of visual spatial attention and shares anterior attentional and semantic areas with semantic priming of a word. Accordingly, auditory shadowing interfered with these tasks. The operations involved in visual priming only involves the visual word form system in the ventral occipital lobe. This task did not interfere with auditory shadowing, which is not dependent on the ventral occipital word form system.

In conclusion, explanations of interference effects and performance limitations in dual tasks should incorporate existing knowledge concerning the organization and functional differentiation and isolation of macroscopic brain structures. This provides at least some constraint on the ad hoc multiplication of resources, but may also explain the variation of task-dependent interference effects.

4.2.4 Conclusions

The computer metaphor of human information processing entails processors (hardware) with a fixed upper limit of capacity, running relocatable programs (software) stored in 'memory'. Fundamentally different from this unbiological metaphor is the conception of the human brain as an associative, flexible, and self-organizing *wetware* system, in which structure and function are intrinsically coupled. Following this wetware conception of the brain, human information processing (including learning) should be considered a highly material- or content-specific process. The brain shows a very complex distributed and heterarchical organization, characterized by a high neuronal interconnectivity. In this network of networks, many subsystems interact and modulate one another's activity and no subsystem can be characterized as structurally dominant. At the same time, we see a large number of systems with rather circumscribed functions connected by a much greater number of different pathways, the great majority of which is reciprocal.

Nervous systems perform a startling range of tasks simultaneously, and with such prevalent order and coherence as to suggest the presence of a soul orchestrating the unity. In this connection, one of the most provocative problems in cognitive neuroscience is to explain this behavioral order without invoking anything analogous to a choir conductor. Much of the high processing performance of the brain originates from its associative wiring, which is necessary for the development of a smart, special-purpose, architecture of brain programs, the local and structural analogues for the more global functional concepts of knowledge and skills. In order to ensure order and to keep behavior goal-directed, given this high associative interconnectivity, the brain must be capable of controlling the degree to which activations spread and modulate or affect one another. This control is achieved on the basis of universal and elementary neurobiological principles, such as mutual or reciprocal inhibition, ensuring the dominance of one brain program over competing brain programs. Extended practice leads to the formation of brain programs, that become already dominant with low levels of activation. This may be the basis of the general difficulty to suppress (or modify) well-learned skills (routines). In skilled task performance, dominant brain programs allow subjects to handle directly and purposively, that is, operate selectively and on the relevant task variables on the basis of very specific trigger inputs.

However, the principle of dominance by mutual inhibition does not prevent all kinds of spreading or interference of activation. Information transmitted and processes by different channels has been shown to 'leak' and reciprocal inhibition can subside by neuronal adaptation. This implies that the simultaneous performance of similar processing operations often will show some interdependency (cross talk and synchronization). The incompleteness of neuronal segregation in combination with the high degree of associative interconnectivity, may serve important functions. First, neuronal overflow may cause coincidence detection, based on which new brain programs may be formed. Second, leakage and adaptation of inhibition may keep the organism more flexible, such that it may change its goals and action plans, e.g., when new and unexpected inputs 'interfere' with current activity. For that aim, the organism even may need an *interrupt* mechanism such as the orienting reflex which inhibits, or overrules, ongoing actions. In the next section, it will be argued that, though the interdependency of subsystems may cause limitations in attentional performance, the intermixing of processing streams is not necessarily detrimental for multiple-task performance.

Macroscopic structural facilities and behavioral capacities have been shown to be related with a high degree of distinctiveness (e.g., Posner et al., 1989). The characteristics of neuropsychological pathologies, for instance, carry a number of radical implications for normal attentional functioning, which cannot be ignored. However, these studies traditionally have played surprisingly little part in the formation of cognitive theories of attention (see e.g., Allport 1989; Posner and Petersen, 1991 for reviews of the neuropsychological and neurobiological basis of attention). As Allport (1989)

convincingly argues, neuropsychological and neurobiological data point to a multiplicity of attentional functions dependent on a various specialized subsystems of which no one appears uniquely 'central' embodying limited capacity. Therefore, human information processing should be understood as highly differentiated, involving many different specialized subsystems with (variable) resource functions. All other things being equal, effects of neuronal interactions will increase with the degree to which the relevant neuronal circuitry is connected. Hence, interactions (mutual inhibition and cross talk or synchronization) among task elements will be most prominent when the involved brain mechanisms are the same or connected. This means that underlying structural discontinuities can be used for defining a more sophisticated framework of functional systems than is at present advocated by multiple-resources theory.

However, the most important basic conclusion of the present section is that the brain does not necessarily need any supervisory control center that decides what elements of perceptual input will be selected for more elaborate processing in order to prevent 'overload' and what activities will be carried out by the organism when incompatible actions are motivated. Although some distributed anatomical areas may be particularly involved in circumscribed varieties of attention (e.g., Posner and Rothbart, in press), these kinds of 'decisions' basically emerge from the basic characteristics of neuronal information processing, i.e., inhibition, facilitation, adaptation, and correlating activity. By selective reinforcement and degeneration of connectivity, this allows the development of a smart topological circuitry, the neuronal embodiment of skills, behavioral coherence, selective attention and capacity limitations.

4.3 When is 'attentional capacity' limited?

In analyzing the underlying mechanisms affecting performance in multiple-task situations, it is a worthwhile first step to consider situations in which attentional capacity seems *not* to be degraded. It will be argued that problems are minimal when tasks allow processing operations to be combined, as opposed to situations in which subtasks have to be independently dealt with. Afterwards, I will describe the task characteristics determining the difficulty of keeping subtasks separate.

4.3.1 Combination and separation

Allport (1980b, 1989), Neisser (1976), and Neumann (1987) point out that the mainstream of psychological data show that processing difficulties in attention do not appertain the combination of operations, but rather dealing with them independently at the same time. This conclusion seems well-founded.

First, it is compatible with our aforementioned knowledge of the brain as a parallel and associative system entailing a high degree of smart interconnectivity, that functions and develops on the basis of elementary processes such as coincidence detection. Functional similarities produce coincident bursts of activity in connected cells, whereas cells responding to different feature constellations in a scene exhibit uncorrelated activity. For instance, superposition of two stimuli in the visual field induces synchronization of cells responding to the same object in the scene, and desynchronization of cells coding for different objects. This is supposed to form a temporal coding mechanism for scene segmentation and figure-ground discrimination (e.g., Engel et al., 1991; Engel, König, and Singer, 1991). Coherent activity on the basis of these functional similarities eventually leads to Hebb-like cell assemblies (see § 4.2.1). This mechanism of temporal assembly coding necessarily entails a highly distributed circuitry with long-range 'horizontal' connections among cells with similar functional properties. This is difficult to combine with completely isolated processes, where simultaneous activations would be completely prevented from spreading to one another.

On a behavioral level, we may expect that this high interconnectivity will promote integrative operations, whereas separation in information processing may be difficult to accomplish. Indeed, an overwhelming number of ecological studies on the area of perceptual information processing (for reviews, Gibson, 1966, 1979) convincingly points out that the subject is tuned to the detection of *invariants*, the higher-order consistencies in the relative order of the stimulus flux (e.g., Gibson, 1966, 1979; Neisser, 1976). Basically, there is no reason to believe that the nervous system performs the same kinds of analyses on the available information as we do in our favorite physical theories. Therefore, biological intelligence cannot be effectively analyzed into physical primitives. It requires an analysis of the way the nervous system is tuned to the higher-order complexities of the world, i.e., covariation and combination of related elements. The incredible processing capacity of the brain probably is indebted to this smart integrative tuning. For example, body movements of terrestrial animals produce an abundance of covarying somato-sensory, visual, vestibular, and possibly (subtle) auditory and olfactory input. It would be very inefficient if the nervous system would process this information completely separately and independently (Gibson, 1966). The ecological studies indicate that human performance will show problems of 'perceptual overload' and illusions only when subjects are constrained in their possibilities to actively explore the available information, e.g., by short exposure times (tachistoscope), head fixations, or when the information artificially is reduced to a few well-defined elementary inputs. Perceptual 'overload' phenomena merely are due to a lack of information rather than to a surplus of information (e.g., De Graaf, 1990).

The tendency to integrate elementary processes in the nervous system is well-illustrated by the existence of so-called *illusory conjunctions* (e.g., Treisman, 1977; Treisman and Gelade, 1980; Treisman and Schmidt, 1982). Whenever display durations

are very short, or attention has to be divided, it may become difficult to perceive separately presented elements correctly. Under such conditions, illusory wholes or objects may be perceived, consisting of the separately presented elements. Treisman and Schmidt (1982), for example, showed that subjects combined shapes and colors of different objects when attention was diverted.

Perceptual grouping and segregation, as previously studied by the Gestalt psychologists, and parallel or serial visual search depends on the degree of similarity of elementary features that specify targets, distractors, or the structures that have to be segregated or grouped. In everyday perception of our environment, we can register a rich array of objects, patterns, and backgrounds in parallel, probably because of the high richness of invariant and covarying perceptual dimensions. By its smart parallel and associative organization, the nervous system aims at detection and processing the higher-order properties of these inputs, thereby integrating patterns of invariant visual information specifying objects (spatial continuity of contours, similarity of orientation and coherence of stimulus motion) and separating them from their context (background).

Allport (1989) argues that for action control, the visual system must be capable of being focussed selectively on any one coherent source of visual information. This coherent information should not necessarily be spatially distributed in the optic array. This has been convincingly demonstrated with overlapping visual displays—the visual analogue of the selective listening paradigm. In case two or more spatially superimposed visual displays, containing outline or moving figures, are presented, subjects are well capable of selectively attending to one outline or moving form, ignoring the other (Allport, Tipper, and Schmiel, 1985; Neisser and Becklen, 1975). Neisser and Beckler (1985), who presented visually similar 'games', only found performance deterioration when subjects must monitor both episodes at once. According to Neisser (1976) and Allport (1989), these results cannot be accounted for by spatial filtering ('attentional spotlight'). The selection of target items seems to result from grouping and anticipation on the basis of intrinsic coherence and structure.

The easiness of combining stimuli may also be illustrated by the contextual effects in visual detection, identification and discrimination. One of such configural effects is the *object-superiority effect* (e.g., McClelland, 1978; Wandmacher, 1981; Weisstein and Harris, 1974). Under certain conditions, the perception of wholes (e.g., object drawings) may be better than that of parts (lines embedded in object drawings). Williams and Weisstein (1978) for example showed that identification of single lines in coherent, object-like contexts can be superior to identification of the same lines when presented alone. Pomerantz (1981) showed that adding a non-informative context to four elements, of which one disparate element had to be located, in some cases dramatically reduced reaction times. Pomerantz (1981) suggests that the addition of context may produce an emerging feature; a higher-order property of the whole, which may be directly perceived. Similarly, in reading printed words, a letter is perceived more accurately when it is

presented as part of a word than when it is shown alone. This is called the *word-superiority effect* (e.g., Reicher, 1969; Wheeler, 1970). Results of Massaro (1985) also indicated an integrated uptake of multiple sources of information only when that information specifies the same event, e.g., such as watching the lips when listening to a speaker.

The way well-trained experts, perceive information in larger wholes ('chunks') is also a good example of perceptual integration (e.g., Chase and Simon, 1973; De Groot, 1966). For example the way we treat configurations of letters and the way chess players perceive configurations of pieces as single psychological units all show capacity enhancement based on our integrative processing potentials.

Allport (1989) reviews divided and selective attention studies showing asymmetrical effects of recombinations of inputs (targets and distractors) and outputs. For example, Glaser and Düngelhoff (1984) presented stimuli consisting of a written word, superimposed on the line drawing of an object. When subjects were requested to *name* selectively either to the word or the pictured object, they found that incongruent but related words interfered with the naming of pictures, but not vice versa. When a *semantic categorization* response was required, related but incongruent pictures interfered with responses to words, but not vice versa. Therefore, in selective and divided attention tasks as well, the degree of compatibility between stimuli, processing operations and responses determines the magnitude of interference effects. This means that in selective attention situations, distractors will cause substantial interference when they are compatible with the class of required responses. Likewise, divided attention situations in which stimuli of one subtask are compatible with responses of the other task will show substantial interference. Some combinations of stimuli and required responses, such as in copy-typing or reading, are relatively easy to handle, whereas other combinations, such as typing from speech or naming objects are relatively difficult (e.g., Shaffer, 1975). The easiest stimulus-response combinations are *ideomotor compatible* (Greenwald, 1970), that is, when the stimulus resembles normally occurring sensory feedback from the response (e.g., auditory-vocal shadowing). The effects of compatibility in the sequences from stimuli to responses in attentional tasks show that mere 'capacity' of brain systems is not the primary limiting factor.

In conclusion, task performance will be optimal when there is coherence or compatibility in the processes that have to be combined and difference or incompatibility in processes that should be kept separate. In the opposite case, attentional performance will be hampered by mutual inhibition and cross talk interference. In that case, task performance will depend further on the availability of other cues enabling effective segregation of processing operations.

4.3.2 Conclusions

The aforementioned data obviously challenge the idea that the nervous system aims at the separated processing of elementary features and that the chance of 'overload' always increases with the number of elementary features. Overload typically seems to result when elements are not part of a coherent (invariant and covariant) whole—that is, when there is a lack of coherent stimulus information. Considering this psychological evidence, the high degree of neuronal connectivity with incomplete isolation of neuronal circuits (see § 4.2) and the fact that parallel and associative processing is one of the basic characteristics of biological cognition, the nervous system must be well-prepared for (or even preoccupied with) integrated information processing. This means that the problem of limited capacity should not be explained by any *a priori* capacity limitation, but rather by the way one major computational problem—i.e., *how to combine massive associative processing power and behavioral flexibility with coherent action control*—is solved. Attentional limitations will occur primarily when coherent perceptual, cognitive, or motor operations have to be isolated or segregated in task performance, whereas the efficiency of information processing and action increases with the degree to which operations can be performed in combination. In general, when there is difference or incompatibility in the processes that have to be combined and coherence or compatibility in processes that should be kept separate, interference will hamper attention performance, and *vice versa*.

The difficulty and requirement of combining or separating subtask elements depends on the available control parameters in the combination of subtasks, jointly with the extent and nature of practice. In § 4.4 the nature of these control parameters will be addressed and § 4.5 will show how practice can take into account these task characteristics in order to enhance dual-task performance.

4.4 Similarity

Because combination and separation are crucial with regard to information processing, the global concept of *similarity* represents an important factor determining the difficulty of coping with the requirements that are specific for dual tasks. The concept of similarity refers to similarities in elementary task characteristics of the subtasks that constitute a dual task. These characteristics may involve: stimulus-response mapping, mental set, semantic or syntactic similarities, processing routines, task and subtask goals, corresponding, correlated or coherent information or actions belonging to subtasks, spatial or temporal similarities, or similarity of color and form. All these dimensions of similarity may affect attentional performance in dual tasks (and in many selective response tasks involving targets and non-targets).

The effects of similarity on time-sharing may act as a two-edged sword, which sometimes may enhance task performance and sometimes degrade it. Similarity which enables the combination of task elements has beneficial effects on task performance, whereas in case processes have to be kept separate, similarity among subtasks will hamper task performance.

4.4.1 Combination: Coherent similarity

Data concerning positive effects of similarity generally indicate that multiple-task performance is enhanced when subtasks share coherent task elements and hampered when subtasks have to be kept separate. Coherence will facilitate combination and/or integration in task performance. That is, when *inputs* (e.g., stimulus locations, -configurations, -movements, -frequencies, -onsets), *processing operations* (e.g., stimulus-response relations, timing mechanisms, decisional heuristics), *actions* (e.g., movement routines, frequencies, amplitudes, directions), or *subtask goals* are coherent, subtasks usually can be combined to a certain degree. Coherent means that task elements are *related, common, corresponding, correlated, or supplementary in connection with the overall objectives of the dual task.* In that case, elements in one subtask can be relevant for the other or the number of mental sets or processing routines (subskills) that have to be activated can be decreased. In the following, this kind of similarity will be termed *coherent similarity.* Coherent similarity will enhance multiple-task performance in comparison with a situation in which subtasks have to be performed separately. For example, while communicating by videophone, visual and auditory information partly will correspond, serving the same purpose (e.g., angry words and an angry face). Furthermore the visual nonverbal information will be supplementary or redundant to the auditive verbal information. In contrast, watching a silent video during a telephone conversation (about another topic) do not share common aims or corresponding or supplementary information, which will increase the difficulty of performing both activities in the same period of time. Similarly, for skilled readers it is not difficult to read aloud at all. Oral reading is a dual task involving a span between eye and voice of several words. In this dual task, the identical words that are read and uttered produce a processing overlap between the reading subtask and the word utterance subtask. Both subtasks are based on the same information and partly on corresponding processing routines.

In an experiment of Chernikoff, Duey, and Taylor (1960), subjects were asked to perform a dual-tracking task, consisting of pairs of subtasks with position control (easy) and/or acceleration control (difficult). Homogenous acceleration control resulted in better performance than a combination of acceleration and position control, in spite of the fact that the average difficulty of the homogenous acceleration control was greater. Quite comparable results were reported by Duncan (1979). He asked subjects to time-share two reaction-time tasks that could have compatible (easy) or incompatible

(difficult) S-R mapping. Hence, the dual tasks consisted of two subtasks with compatible mapping, incompatible mapping or one with a compatible and the other with an incompatible mapping. It appeared that the dual task consisting of two incompatible tasks provided better performance than the combination with one compatible and one incompatible task. This result shows a 'second order compatibility', emerging from the combination of goals of the two subtasks: a (between-subtasks) compatibility of (within-subtask) compatibility. Klapp (1979) reported superior time-sharing in simultaneous rhythmic activities when temporal patterns were compatible, and Peters (1977) showed that the magnitude of interference effects in two motor tasks decreased with the degree to which the concurrent rhythms could be made compatible. Korteling (1991) showed that subjects performed better in a dual-compensatory tracking task when the pointers of both subtasks moved synchronously instead of independently, which means that individual subtasks provided supportive information with regard to the concurrent subtask.

All these studies show beneficial effects of coherent similarities between tasks. Coherent similarities, such as synchronization of movements or between-task compatibility of a mental set or processing routine, serve the performance of both subtasks, thereby enabling subjects to combine the subtasks. The *selective* activation of the appropriate performance routines becomes then less critical.

The described results run counter resource conceptions, which always predict performance decrements with increasing content-independent similarity (i.e., common resources). In § 4.5, I will introduce the underlying mechanism based on which people can (learn to) combine such tasks.

4.4.2 Separation: incoherent similarity

Allport, Antonis, and Reynolds (1972) argued that subjects' inability to pay simultaneously attention to two similar tasks derived not so much from a limited-capacity central processor, but more simply from confusing two similar but unrelated messages. The studies and conclusions discussed in the previous sections, all support the notion that the brain is well-prepared for, and preoccupied with, associative and integrative processes. This characteristic may lead to degraded performance in case similar processes have to be separated. Separation is needed when subtasks are incoherent. Apart from the fact that separation in itself is detrimental, separation may become extra difficult when the subtasks contain similarities on a superficial or representational level. All kinds of similarity among subtask-elements—termed *incoherent similarity*—may then degrade task performance. For example, watching a silent video during a telephone conversation about another topic entails no common aims or corresponding or supplementary information. Following both the auditory and the visual task will be very difficult. When in such tasks similar concrete elements (classes of objects, words, or concepts) occur, incoherent

similarity among subtasks is increased, increasing the difficulty of keeping the tasks separate.

A study in dual-task word categorization, conducted by Navon and Miller (1987), demonstrated emerging confusions and cross talk among the two visual-manual systems when targets of one task belonged to the same category as nontargets of a concurrent task. The classic example of this kind of conflict is the Stroop task (Stroop, 1935), in which verbal information interferes with the subject's ability to name the ink color in which the word is printed. Another example of negative effects of incoherent similarity derives from the *proximity compatibility* principle, i.e., the compatibility between similarity at one level of processing and similarity at another. In a dual-axis tracking task, in which similarity at the stimulus level is different from that at the response level, performance probably will be hampered by cross talk, that is, the degree to which error in one subtask is affected by unwanted control responses of the hand controlling the other task. In dual-tracking tasks, Fracker and Wickens (1989) found that cross talk, may increase when there is a mismatch between display and control integration, that is tracking two separate single-axis pointers with one two-axis control stick, or tracking one two-dimensional pointer with two single-axis sticks. Although this cross talk was not accompanied by increasing tracking error, subjects were found to adopt a more cautious tracking strategy. Hirst and Kalmar (1987) conducted a series of multiple-task experiments in which they combined cognitive tasks such as spelling and arithmetic. They found greater dual-task decrements when subjects performed either a pair of spelling or arithmetic tasks than when they performed spelling and arithmetic together. In a pair of spelling or arithmetic tasks, superficial or raw elements, such as letters or digits, belonging to one subtask may easily be confused with similar elements of the other subtask[2]. Finally, it has been shown that the ability to selectively process one of two messages or to shadow two simultaneous messages, is disrupted by semantic similarity between the two (Hirst, 1986; Shaffer, 1975; Treisman, 1964). Hirst (1986) points out how distinctive superficial acoustic features of two verbal messages can facilitate the subject's ability to deal with these separately. Therefore, *consistent differences* between two tasks can be used to keep them separate (see § 4.5.2).

In general, degrading effects of similarity appear when subtask inputs, processing routines, actions, or goals are incoherent with regard to the overall task objectives. This means that the subtasks have to be kept separate. In that case, similar features, which play a different role in the different subtasks, may disturb this process of subtask separation. In general: when *incoherent similarity* is increased (e.g., when two unrelated

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[2] Although a pair of homogeneous spelling or arithmetic tasks requires the same 'mental set', which will increase the degree of coherent similarity, apparently, confusions caused by similar and not sufficiently distinctive features dominated.

verbal tasks share semantic or syntactic similarities, or when two arithmetic tasks share the same numbers, etc...), subtasks have more features in common, such that it becomes more difficult for the subject to segregate them. The subject is then required to perform extra and more precise mapping operations between stimuli, processing operation, and responses belonging to the subtasks. In order words, the *selective* activation of the appropriate performance routines becomes more critical. When people fail to select and activate the proper routines, processing operations may interfere or be directed to the wrong subtask. Subjects may then unintentionally combine elements of different subtasks, resulting in a mutual disruption of subtasks. This kind of error mostly is referred to as *cross talk*, *outcome conflict*, or simply *confusion*.

In this connection, incoherent similarity may also be termed *representational similarity* (Korteling, 1993a) because it only involves the raw, superficial elements of subtasks. As opposed to the content-independent, and rather crude framework of resources, incoherent similarity may refer to all concrete, content-dependent, similarities among subtasks. Different kinds of similarity may work out in a cumulative, or even multiplicative way. Spatial proximity, for example, will substantially aggravate the negative effects of superficial similarities of subtask elements. In contrast, spatial proximity may enhance the cooperative effects of coherent similarities. Accordingly, possible effects of coherent and incoherent similarities always should be considered in combination.

Content-dependent interference cannot always be captured by multiple-resources theory. For instance, if a right-hemisphere and a left-hemisphere task involve information specifying the same concrete entities (e.g., buildings, places, concepts, countries, famous people, etc.), content-dependent effects may be expected, regardless of the 'resources' involved. Also the Stroop phenomenon (Stroop, 1935) is a fair example of content-dependency in information processing, because the semantic/verbal content of color words interferes with the perceptual content of colors.

In § 4.5, I will point to mechanisms by which people cope with incoherent similarity.

4.5 Training: capacity elaboration

As was argued in the previous chapter, a major problem of resource theory is that it assumes that limited capacity is fixed. Researchers who adhere to resource theory are not interested in how the organism adapts to meet multiple-task demands, rather they are interested in the trade-off between performances on the subtasks of an organism that did not benefit from practice or experience. With fixed capacity, skill improvements with practice are mainly explained by the development of more efficient information processing strategies, i.e., strategies that do *not* consume resources. Therefore, as was previously argued, the concept of *automaticity* exists in close connection with resource

theories, though it is not well specified *why* and *how* automatic activities do not require resources. Mutual relationships among subtasks—that is, interactive, associative, and competitive elements in information processing—are hardly addressed. Whereas the fixed capacity approach can be regarded satisfying for simple visual search or letter identification tasks, fixed resource explanations seem untenable with reference to complex or subtle skills, progressing over years of training, such as: chicken sorting, perfume selection, mammography diagnosis, sonar perception, chess playing, composing, etc. It seems rather far-fetched to explain the development of complex cognitive skills, such as writing scientific manuscripts, by concepts like automaticity, which is conceived as 'unconscious', 'stimulus driven', pre- or postattentive, and not under direct 'subject control'. In such tasks it seems more appropriate to explain performance improvements by the acquisition of knowledge and true new skills; that is the formation of brain programs that are sensitive to new aspects or configurations in the input, and brain programs that can handle and manipulate these kinds of information appropriately.

The brain, is a highly flexible, elastic, and adaptive system. This means that the manner of task performance qualitatively may alter with practice. A skilled individual may have learned to detect new stimulus constellations and execute new patterns of actions, not just do old things quicker, intermittently, or without attention (pre- or postattentive). The neuronal commands of a skilled piano player are different from those when he was a novice. Therefore, in opposition to the fixed capacity notion, Neisser (1976) and Hirst (1986) conjectured that attentional capacity is not fixed, but should be conceived exclusively a matter of *skill*. These authors took as their starting point the substantial changes that occur with extended practice in normal (i.e., consistent) tasks. Hence, their interest was in what skills allow an individual to meet the shown level of performance and how these skills change with practice, not how he or she allocates resources. Neisser (1976) furthermore argued that there are no fundamental limits to this performance capacity. This conviction stimulated courageous experiments (e.g., Hirst et al., 1980; Spelke et al., 1976). Spelke et al. (1976) report performance of two subjects who, after prolonged training, were able to copy unrelated words at dictation, whereas they read and understood stories. For that matter, already in the previous century, Solomons and Stein (1896) demonstrated that people could learn to read while writing at dictation. These results show that by sufficient amounts of training, subjects can develop large improvements in time-sharing efficiency. Allport, Antonis, and Reynolds (1972) documented piano players who could shadow prose while sight reading material of varying difficulty. Shaffer (1975) reported that a highly practiced typist was able to type visually presented material while concurrently reciting nursery rhymes or random letters or shadow prose with only about 10% concurrence costs in terms of typing speed and accuracy.

However, the view of unlimited capacity, given sufficient amounts of training (e.g., Neisser, 1976), probably is not tenable in this form (Neumann, 1987). Some tasks seem

to resist months of training (e.g., Gottsdanker and Stelmach, 1971; Salthouse and Somberg, 1982) and with tasks characterized by a varied mapping of stimuli to responses, no learning appears to develop at all (e.g., Schneider and Fisk, 1982)[3]. Despite their considerable effects of training, even Hirst et al. (1980) had to admit that notwithstanding their subjects understood what they were writing as well as what they were reading, *their understanding seemed less than complete under these conditions* (p. 114).

Below, I will show that in one respect Neisser and his colleagues probably were right and in another they were wrong. Starting with a general cognitive neuroscience framework concerning skill development with training, it seems that attentional capacity can increase almost infinitely only when, on the basis of coherent similarity the skills underlying subtask performance can be combined or integrated into a common higher-order skill. In contrast, when subtasks show no coherent similarity, or a high degree of incoherent similarity, skills must be kept separate and performance enhancement will be limited to the degree individual single-task skills are learned and the tasks contain distinctive features to keep them segregated.

4.5.1 Basic mechanisms of skill development

In normal—and thus consistent—tasks, practice will lead to the acquisition of knowledge and skills allowing enhanced task performance. It may be considered self-evident that also dual-task performance will increase with the amount of subtask skill (all other things being equal). Resource theories (e.g., Kahneman, 1973; Navon and Gopher, 1979; Wickens, 1984, 1991) have not sufficiently detailed the structure and nature of resources and underlying mechanisms to provide insight into practice effects, with respect to single- as well as in dual-task performance.

A connectionistic model

Schneider and Detweiler (1988), however, provide a connectionistic model for skill development in both single- and dual-task processing (see also: Detweiler and Schneider, 1991). This model, which provides a mechanistic explanation for the two-process theory (see § 2.4 and § 3.4.1), particularly addresses the issue of transfer from single- to multiple-tasks. With regard to single-task performance, Schneider and Detweiler (1988) suggest a gradual learning process consisting of five phases of skill acquisition. Skill

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[3] Although, it is reasonable to argue that with varied mapping one cannot speak of extended practice of the *same* task, because the *critical* task-elements typically are continuously changing. Automaticity, or significant skill development, *of course* will not develop when the training involves brief performance sessions, in each instance with regard to another task, i.e., a task in which the critical invariants change.

learning starts with a phase, in which processing is very effortful, requiring many shifts of attention and monitoring of sets of processing activities, and ends with a phase, characterized by automatic processing. In this automatic phase, sets of stimulus processing activities are directly and quickly transmitted via a limited-capacity 'inner loop' to response modules, without the requirement of attention switching. In their model, information need not all pass through a central executive, rather functions ('processing regions') can intercommunicate directly. However, there is a central control structure that modulates transmissions within and among regions in order to limit interference. Although this model is feasible on a coarse level, the basic assumptions are simplified with regard to current neurophysiological and neuroanatomical knowledge, leaving obvious questions unanswered. What, for example, is the brain mechanism represented by the inner loop and what is the control system modulating transmissions? Why is the number of modules so limited? What role is there for coincidence detection, one of the most universal operations of the brain? Finally, the conceptions of Schneider and Detweiler still originate from the tenuous fixed-capacity assumption.

Special-purpose and general-purpose brain programs

On the basis of the previous conceptualizations, connectionistic frameworks, like that of Schneider and Detweiler (1988), may be adapted such that they become more in line with our knowledge of brain functioning. This means that skill development should be conceived as a gradual process of adapting and tuning brain programs to the invariants of the task, that is the (higher-order) consistencies among input processes, central processing operations, and responses. With training, brain programs become sensitive to new aspects of, or configurations in, the input. Furthermore, new brain programs are developed to handle these kinds of information appropriately, and the system may program new potential action sequences.

More specifically: skill development involves the formation of *special-purpose* brain programs, that need only low levels of activation to dominate (by mutual inhibition, see § 4.2.1) other, potentially interfering, processes. When these dominant brain programs exist, task performance will be more direct, selective, and purposive.

How are these special-purpose programs acquired? When a task is new, performance is a slow, serial, and effortful process, which may be understood as the operation of *general-purpose* brain programs, or skills. These general-purpose brain programs are cortical networks with an abstract algorithmic character (i.e., relatively content-independent) serving various purposes (flexible) and are more indirectly related to specific tasks. General-purpose programs enable a person to perform classes of tasks for which the specific perceptual, cognitive, and/or motor routines have not been acquired yet. General purpose and special purpose brain programs may be conceived the analogue for declarative and procedural knowledge, respectively, in the cognitive domain

(Anderson, 1982, 1987). During initial practice, general purpose activity alters neuronal activation thresholds (i.e., selective attention) and generates and controls activity on the basis of global conceptions. In general, activity always generates feedback. Therefore, during training, the stimulus-related activation of general-purpose programs will generate positive and negative feedback, or 'knowledge of results' (e.g., Adams, 1979; Schmidt, 1975). In the nervous system, the coincidence and covariation of stimulus input, efferent general-purpose activity and afferent feedback will lead to creation, modulation and adaptation of neuronal Hebb-circuitry[4]. The magnitude of changes that are made are proportional to the size of the difference between actual and desired output (e.g., Rumelhart, Hinton, and Williams, 1986). In other words, early in training, the effect of feedback will be maximal and changes in neuronal circuitry will be the most sizable. As the appropriate neuronal assemblies develop, the error gets smaller and therefore so do the changes made to the connections.

In summary, general purpose activity controls behavior when the more efficient special-purpose brain programs have not yet been sufficiently developed to dominate. However, on the basis of enduring consistent activation and by incorporating feedback, special-purpose circuitry gradually will become more dominant, requiring low activation levels in order to determine behavior. Smart special-purpose brain programs are direct, selective and purposive and—once facilitated by a task situation and triggered by a specific stimulus set—these programs will control behavior, ensuring an efficient and coherent course of action. When control is taken over by efficient special-purpose brain programs, the number of elementary operations required to perform the task will decrease. Hence, the number of neural networks necessary to perform the computations will decrease. Subjectively, this may be experienced as effortless and subconscious. Objectively, this may be demonstrated by PET data, indicating that repetition of the same performance leads to reduced blood flow in the neural areas that are originally required to generate the response (Fiez and Petersen, in press). It may be assumed that this principle will apply to psychomotor and cognitive tasks in general (Posner and Rothbart, in press).

The formation of special-purpose brain programs also entails the *coupling* of already existing routines or skills. Fitts (1964) already suggested that skills are built up from many pre-existing, highly developed processing subroutines. With single-task learning, these subroutines are organized into larger and larger units (see also Neumann, 1987). An example of reorganization of existing skills is that car drivers may in the long run learn to attend to and incorporate rather simple and basic information, such as head movements of other drivers, in their decisions when approaching an intersection. It may be supposed that the gradual transition from general-purpose to special-purpose dominance is a bottom-up process, starting with the formation or reorganization of

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[4] This process cannot effectively take place in varied mapping tasks.

elementary smart mechanisms followed by the formation of higher-order special-purpose programs, which handle task variables of increasing complexity. These complex task-variables may be very task-specific e.g., chunking in experienced chess players (see § 4.3.1). When tasks are complex enough, the transition from general-purpose to smart special-purpose brain programs or skills, capitalizing on increasingly more subtle and higher-order task-elements and relationships among these elements, may progress over several years of training.

Automatic and controlled processing revisited

According to the presently advocated cognitive neuroscience orientation, the process of what is called 'automatization' is the transition from general-purpose to more dominant and specific special-purpose skills or brain programs that are directly tuned to the critical task elements. This direct tuning implies that, special-purpose programs will only be activated by very special input constellations. These constellations include a general facilitation by the overall task situation (e.g., instructions) of a set of related special-purpose skills, and specific trigger stimuli selectively activating a special-purpose skill of this set. The necessary pre-facilitation prevents that this circuitry can be triggered by irrelevant inputs, thereby interfering with task processes for which they are not intended. For example, when driving a car, the red lights of braking lead-cars may trigger braking responses (and inhibit gas pedal pressure). In contrast, this behavior will not be triggered when sitting in a car as a passenger or watching a movie with braking cars. Also the use of general-purpose brain programs intended for other classes of behavior than vehicle control, will not be dominated by the execution of special-purpose vehicle control skills. For example, when braking, people still can listen to the radio, figure out what route they will take or how far they still have to drive before arrival at their destination. However, if experienced drivers want to use general-purpose programs for vehicle control while driving—like they did when they learned driving—this will be severely disturbed by the continuous activation of already acquired special-purpose skills for car driving. This may also explain the difficulties people encounter when they have to alter behavior in a well-trained task situation, dominated by special-purpose skills. In that case they must effectuate general-purpose skills in order to suppress or modify the execution of dominant special-purpose skills. This usually is difficult because these skills are easily triggered by the task situation and tend to dominate behavior. However, because the *appropriate* special-purpose brain programs for the present *new* task situation are lacking, general-purpose skills can control and overrule these skills. Only extended training may produce new special-purpose skills that are strong enough to dominate over the old inappropriate skills. Most sportsmen can tell how difficult it is and how much 'self-control' it requires to replace an old habit by a new one. In sport, it is a well-known statement that performance will degrade when one starts 'to think' about ones actions.

Other examples of conflict among special-purpose and general-purpose brain programs are the difficulties of knowledge elicitation in experts or imitating a novice in a perceptual-motor task. In an review of the literature, Shanteau (1992) points out that research findings on balance have shown that experts do not use more or more general information than non-experts when taking decisions ('Information-Use hypothesis'). They are, however, better in discriminating relevant from irrelevant information and weighing the selected elements. The diagnostic value of cues differs from situation to situation. Non-experts lack the specific skills to handle this context dependency of cue diagnosticity. Compared to experts, they tend to over-generalize available cues.

With regard to the theoretical orientation proposed here, it is thus significant to realize that special purpose programs will dominate over general-purpose programs for a specific task when both cover the same area, that is: special-purpose brain programs need lower levels of activation in order to inhibit competing programs. Of course special-purpose and general-purpose skills can very well co-exist and cooperate when both are aimed at different levels of the same task or at different tasks, i.e., writing and thinking what to write, steering and route planning, steering and calculating. In other words: when both refer to the same level, general-purpose brain programs can only function 'effectively' when appropriate special-purpose programs are lacking.

4.5.2 Development of specific multiple-task skills

The acquisition of special-purpose brain programs (for single tasks) generally will improve *dual-task* performance when this (partly) involves the same single-task special-purpose brain programs. However, as has been pointed out in the previous chapter, some components of performance gain in dual tasks do not result from skill development in single-task performance. In other words, exclusive single-task training is insufficient to reach single-task performance levels in a dual task (e.g., Schneider and Fisk, 1982, 1984). Even when one or both subtasks are extensively practiced—with a constant relationship between stimuli and responses—extensive dual-task practice may appear necessary to simultaneously perform the dual task with little deficit. Otherwise, it is also possible that tasks that do not allow 'automatic processing' in the classical sense, still can be performed simultaneously with little or no interference (Hirst et al., 1980; Spelke et al., 1976). In addition, in specific combinations, such automatic tasks may cause or suffer significantly from interference (e.g., the Stroop tasks). In previous sections (§ 4.4.1 and § 4.4.2), I have pointed out that dual-task performance is substantially determined by the idiosyncracies of the available control parameters in the combination of subtasks. In this connection, the next two sections will address the possible mechanisms involved in the acquisition of skills related to this combination.

Coherent subtasks

A dual task is more than the sum of two (isolated) part-tasks. The difference between the two may be expressed in terms of the harmful or beneficial aspects of similarity. Problems in multiple-task performance may be effectively coped with when subtasks share coherent processes with regard to the available information, the processing routines, actions to be performed, and task goals. This may, for example, be so when similarity involves related inputs, such as synchronously moving cursors in a dual-tracking task. In dual tasks consisting of coherent subtasks, subtasks usually can be combined to a certain degree (see § 4.4.1).

One important observation in this respect is that in complex everyday tasks, such as bicycling, the brain's potential to handle information from multiple sources appears to be very large compared to the limits of attentional capacity in apparent simple laboratory tasks such as dichotic listening or pressing a button in response to a tone while engaging in a tracking task. This difference may be explained by the high degree of *coherent similarity* within complex everyday tasks, i.e., the consistent (higher-order) relationships that exist between many elements of these tasks. In most laboratory tasks e.g., the dichotic listening task or a combination of a tracking task and a reaction-time task, usually no such relationships are provided. In everyday automobile driving, however, manipulation of the gas pedal, the clutch pedal, the brake, but also mirror use all are related. For example, pressure of the clutch and brake pedal is inversely related to pressure of the gas pedal. Furthermore, during driving on straight roads, all potential cues for lateral position, lateral speed and heading rate of the vehicle specify the same required steering wheel actions (Riemersma, 1987). That is, both subtasks are based on the same information and partly on corresponding processing routines. Such relationships between dual-task components probably are a *boundary condition* for the high proficiency of people in everyday skills.

Whether or not a person may *learn* to perform complex tasks effectively, is a matter of whether or not the task as a whole is coherent in a consistent manner. The effectivity of consistent higher-order relationships among task components has been demonstrated in the laboratory. Fisk, Oranski, and Skedsvold (1988) showed that skill acquisition was substantially enhanced by global consistencies in the relationships among task components, which overruled more local inconsistencies on the level of individual stimuli. This fits remarkably well with the previously summarized aspects of brain organization, containing smart special-purpose programs, the mechanisms capable of handling subtle or higher-order relationships in the available information.

As was suggested before, single-task training may result in the development of special-purpose skills, which require low levels of specific activation in order to dominate behavior (by inhibition of related and potentially conflicting mechanisms). In addition existing special-purpose subroutines may be re-organized into larger units, tuned at the

higher-order characteristics of the task ('chunking', see § 4.3.1). Also with regard to subtasks sharing consistent relationships, such integrative processes are not very difficult to imagine. On the basis of consistent relationships between subtasks, individual single-task skills (or brain programs) may be associated and integrated into a common special-purpose skill of a higher-order. This new special-purpose skill capitalizes on specific peculiarities of the combination of subtasks.

The execution of such common higher-order skills will be much more efficient than the separate execution of lower-order skills. When skills have to be executed separately, there will always be problems related to selection, segregation, and coordination of goals and skills. For example, competitive inhibition among simultaneously activated brain programs may ensure a certain degree of coherent task performance without cross talk interference. However, as was argued before, action control by mutual inhibition leads to capacity limitations. In short, when subtask elements are characterized by coherent similarity, subjects may integrate them into one higher-order task, such that the limitations inherent to the organization of different processes are overcome. Hence, the dual task will be performed, to a certain degree, as a single task (see § 4.5.3). When it is possible to combine coherent subtasks, skill integration may thus become a significant determinant of skill acquisition, and thereby of dual-task performance.

According to Hirst (1986), integration of task elements into one higher-order skill can involve stimuli, central operations, and/or response processes. As opposed to single-task performance, only in dual-task performance, spreading or correlated activity among (to-be-integrated) brain programs may facilitate task performance. Therefore, such integrative processes can only take place with dual-task training. On the basis of these notions it can be predicted that beneficial effects of dual-task training will increase with the degree of coherent similarity among subtasks. Furthermore, training should aim at the integration of coherent similarities among subtasks.

Incoherent subtasks

When two incoherent or unrelated tasks make up a dual task, a person necessarily has to deal with them independently. As a matter of fact, there is nothing to relate or integrate at all. Hence, the underlying skills (brain programs) cannot be combined or unified to a smaller number of superordinate skills. In the literature, problems concerning dual-task performance are typically addressed from this perspective of unrelated subtasks.

As was pointed out in § 4.5.1, single-task training may show limited transfer to dual-task training. According to Schneider and Detweiler (1988), automaticity in single-task performance does not necessarily mean that it is possible to combine tasks without deficit. In order to account for the degree of transfer from single-task training to dual-task performance, the general differences between single tasks and dual tasks consisting of unrelated subtasks has to be analyzed. This will lead to the identification

of behavioral mechanisms in dual-task situations that do not occur in, or are not as critical for, single-task situations. Schneider and Fisk (1982), for example, suppose that dual-task deficits with automatic subtasks may be due to some small costs resulting from 'setting up' an automatic process, while the execution of the processing itself may not require any resource input.

The literature suggests a number of coping mechanisms specific for dual tasks that do not involve relationships among subtasks (e.g., Neumann, 1987; Schneider and Detweiler, 1988; Wickens, 1989). These processes can be divided into two main categories. The first category involves utilizing optimal *strategies* with respect to the specific dual-task requirements, i.e., time scheduling, utilizing non-interfering processing faculties, letting go of unnecessary demanding performance strategies. The second category is more basic and involves the *segregation* of skills such that interference or cross talk among subtasks is minimized (Hirst, 1986; Neumann, 1987; Wickens, 1989).

Strategies

Because the employment of strategies goes beyond the scope of the cognitive neuroscience framework presented here, this first category of specific dual-task processes will be briefly summarized. With respect to the first category, Schneider and Detweiler (1988) suggest three performance strategies that are exclusively relevant in dual-task performance: 1) Delaying less critical task elements while performing the more critical subtask, that is, anticipating on, or preprocessing, more critical task elements prior to onset of these elements; 2) Performing one subtask in a manner that does not require processing mechanisms required for the concurrent subtask; 3) Letting go of unnecessary high-workload strategies, which means that with increasing skill-development, a person should not adopt a strategy as if he still were a novice. In other words, let a skill do its work. Another mechanism mentioned by Schneider and Detweiler, i.e., shortening inner-loop transmission times, is difficult to combine with current knowledge of the brain.

Subtask segregation

The second category of exclusive dual-task effects of training involves a gradual process of specialization and segregation of brain programs or skills. As we have seen in § 4.4.2, performance of dual tasks consisting of incoherent subtasks may be hampered by all possible aspects in which the subtasks are similar. In general, the success of performing subtasks characterized by incoherent similarity depends of the degree to which relevant processing operations are kept distinct or isolated, such that mutual interference is minimal. As was argued in § 4.3.1, the brain is not particularly aimed at keeping similar information processes separate. Both mutual inhibition and cross talk may disturb processing operations in related mechanisms. In addition incoherent similarity may

produce synchronized neural discharges on the basis of which the brain may associate representations that should be kept distinct. Therefore, the execution of similar but unrelated task elements needs the development of isolated special-purpose brain programs.

In § 4.5.1, performance in untrained tasks was conceived as determined by non-dominant general-purpose brain programs. During training these brain programs are tuned and reorganized on the basis of the (consistent) critical elements of tasks. With practice, this results in the development of more task-specific, higher-order, and dominant skills, i.e., special-purpose brain programs. There is no reasonable contention against the general principle that the development of special-purpose subskills will enhance the simultaneous performance of these same skills in a dual task, just because of the higher effectivity of these skills. However, there is more at stake with the transition from general purpose skills to special-purpose skills. According to Neumann (1987), the more general the available skills, the greater the chance that the to-be-combined actions will depend on the same brain programs and therefore cannot be performed concurrently. This means that interference effects in dual tasks consisting of incoherent subtasks, will decrease with the specificity of subskills. The development of more specific skills will decrease their potential degree of overlap and thereby avoid confusion effects. Therefore, on a basic level, single-task training may enhance the process of skill segregation in dual-task conditions.

With respect to complex everyday-tasks, positive effects of extended practice or low degrees of incoherent similarity have been experimentally substantiated. Brown and Poulton (1961), for example, showed that experienced drivers can perform difficult mental calculations while they drive. In this case, both subtasks are unrelated, well-trained in isolation and may be supposed to depend largely on completely different input, processing, and output structures.

However, when tasks show incoherent similarities, exclusive single-task training may not be enough to reach a sufficient degree of segregation in information processing. With incoherent similarity, a significant proportion of dual-task practice may be required in order to learn to specify, select, and activate the proper skills for each subtask. In addition, with incoherent similarity among two well-trained subtasks, dominant special-purpose brain programs may be triggered by the wrong task elements resulting in severe interference. An everyday example of such kind of conflict may be experienced on the tennis court, when playing alone against two partners. When both these partners accidently play a ball at you at the same time, it is surprisingly difficult to select just one ball in order to hit it back, neglecting the other. It seems that one cannot suppress the tendency to hit both balls. Such conflict will be less severe when the degree of incoherent similarity is low (different colors or spatial or temporal segregation of balls) reducing the chance that inappropriate dominant responses are triggered. Some research may be done to test the hypothesis that the transfer of single-task skills to dual-task skills decreases

with increasing incoherent similarity and that beneficial effects of dual-task training will increase with the degree of incoherent similarity among subtasks. Training strategies should aim at the segregation of subtask elements such that cross talk and mutual inhibition may be precluded.

When the degree of incoherent similarity is high, subtask segregation has to be accomplished on the basis of control parameters that consistently differentiate between the two subtasks. This may pertain to relatively subtle differences among task components (Allport, 1989). Hirst and Kalmar (1983), who employed a dichotic listening paradigm, found that subjects could distinguish both auditory subtasks on the basis of distinct phonological features. For example, in one of the auditory messages, all of the words began with fricatives, while in the other, the words began with plosives. This skill also improved selective attention performance. When such disjunctive features are absent, it may become difficult to learn to segregate two tasks. Because such differences are related to the to be separated subtasks in a consistent manner, this was termed *consistent difference* (§ 4.4.2). In conclusion, when tasks are characterized by incoherent similarity, the extent to which cross talk interference can be coped with by training will depend on the availability of other control parameters enabling segregation of subtasks or task elements, i.e., consistent difference. Consistent difference will be a major performance determinant in selective response tasks, such as Stroop-like tasks. Therefore, dual-task training may particularly enhance skill segregation, which may be relevant for subtasks characterized by incoherent similarity, but also by consistent difference.

4.5.3 What is a single task?

It can be argued that many everyday dual tasks, such as oral reading, piano playing, or bicycling, entail such a high degree of internal compatibility and natural relatedness that, after sufficient practice, they are easily experienced as single tasks. The idea that we consciously can do only one thing at once with our limited controlled processing capacity probably may be due to the fact that we perform most complex tasks as one or a few wholes. When skill integration reflects the gradual change from separate performance of single routines or subskills to integral performance of higher-order skills, this one-thing-at-a-time experience thus may be regarded as the result of skill integration.[5] This hierarchical conception of units (skills, tasks, but also stimuli), consisting of elements and organized into larger wholes, shows that multiple-tasks theory only differs from single-task theory in its more sophisticated way of task- and performance analyses.

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[5] This means that a completely integrated dual task is the same as a single task, because the underlying skills have become part of one higher-order skill. When an integrated dual task is factually a single task, a non-integrated dual-task can be considered as a combination of two non-integrated single tasks—i.e., a combination of two completely integrated dual tasks.

Following this viewpoint, it is rather arbitrary to count things like tasks, skills, or stimuli without an analysis of the situation and the required behavior as well. That is, you cannot give definite answers on questions such as: 'how many stimuli together make up a running train consisting of two railway wagons, each containing three doors, four wheels, five windows, etc.?' 'how many subtasks are involved in watching a football game?' Similarly, the very notion of being aware of 'a single thing' is far from clear (Neisser, 1976).

Therefore, in order to understand the processes underlying multiple-task performance, one should first devote ones energies at the *task ecology*, i.e., analysis of the task as embedded in a task environment. This should involve an analysis of the overall task mission, available information in relation to the task goals, required decisions and actions, feedback loops, and relationships among these processes. Only afterwards, one can reason which underlying processes may determine task performance.

4.6 Discussion and conclusions

Nervous systems perform a startling range of tasks simultaneously, and with such prevalent order and coherence as to suggest the presence of a soul orchestrating and supervising this unity. In this connection, one of the most provocative problems in cognitive neuroscience is to explain behavioral order without invoking anything analogous to a choir conductor located somewhere centrally in the nervous system. Current knowledge concerning the neurobiological aspects of cognition, indicates that it is the smart, purposive and unimaginable high degree of associative interconnectivity of neurons that gives rise to our amazing information processing capacity and flexibility. In combination with the goal-oriented character of biological information processing, this may form the basis of a theoretical explanation for the organization and limitations of attentional capacities, without needing central controllers as an essential 'explanatory' construct. The reasoning is briefly summarized below.[6]

In order to be able to handle a multitude of stimulus elements, biological systems process information in an associative, parallel, and integrated manner. This processing strategy is based on a high degree of associative *interconnectivity* in the nervous system, allowing coincidence detection, the detection of the invariant and covariant aspects of inputs, central processing operations, and response processes. In addition, associative interactions allow an organism to be *flexible*, i.e., to change or inhibit ongoing operations when other inputs intervene or to adapt or develop the brain programs controlling behavior. The organism even may need an interrupt mechanism, overruling current

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[6] The present chapter did not deal with (peripheral) bio-mechanical interference.

operations, when new and unexpected inputs emerge. Associative processes may explain many specific interference effects and the interrupt mechanism may explain unspecific interference effects, mentioned in the previous chapter. Given this associative architecture of the nervous system, cross talk and neuronal overflow will frequently occur. This is particularly relevant for active, locomoting organisms, for which stimulus conditions frequently change, such that potentially competing operations continuously are activated. Therefore, control mechanisms are needed to ensure that behavior remains ordered, i.e., *goal-directed*. It is argued that this control is achieved on the basis of universal and elementary neurobiological mechanisms, such as mutual or reciprocal inhibition, ensuring the dominance of one brain program over competing brain programs. The capacity to perform multiple-tasks may then be limited because ongoing operations inhibit other possible operations.

The brain does not necessarily need any supervisory attentional control center that decides what elements of perceptual input will be selected for more elaborate processing in order to prevent 'overload' and what activities will be carried out by the organism when incompatible actions are motivated. Although some distributed anatomical areas may be particularly involved in circumscribed varieties of attention, these kinds of 'decisions' basically emerge from the basic characteristics of neuronal information processing, i.e., inhibition, facilitation, adaptation, and correlating activity. By selective reinforcement and degeneration of connectivity, a smart topological circuitry of brain programs is developed. These brain programs are the local and structural embodiment of the more global functional concepts of knowledge and skills, i.e., the control structures building long-term memory[7]. The general principle of this orientation is that two operations performed simultaneously by the same or heavily interconnected circuits will produce specific interference or interaction effects on the basis of elementary neurobiological mechanisms such as mutual inhibition.

The high degree of neuronal connectivity with incomplete isolation of neuronal circuits and massive parallel and associative processing suggests that the nervous system must be well-prepared for (or even preoccupied with) integrated information processing. At the other hand, the brain is not particularly good in keeping similar information processes separate. Both mutual inhibition and cross talk may disturb processing operations in related mechanisms. Also on the basis of psychological evidence, it can be argued that attentional limitations will primarily occur when perceptual, cognitive, or motor operations have to be isolated or segregated in task performance, whereas the efficiency of information processing and action increases with the degree to which task routines can

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[7] Brain programs were defined as neuronal control structures or networks modulating and redistributing incoming neuronal activation patterns and coding for a number of potential output or action sequences (parameter specification).

be performed in combination. Problems typically emerge when subjects have to simultaneously activate (i.e., select, program, control and monitor) completely different processing routines in order to reach the accessory distinct goals. In contrast, the efficiency of information processing usually increases with the degree to which task elements are related or coherent, such that subtasks can be performed more or less as a whole (i.e., skill integration). In the latter case, the typical complications of dual tasks even may disappear; oral reading is usually not experienced as a dual task.

According to the conception of the brain as a flexible wetware system, owing its power to survive from its incredible associative complexity, content-dependent integration of coherent processes and interference among incoherent processes will be the rule. This means that limited-capacity phenomena can be explained by the way *the brain has to combine its massive associative processing power and behavioral flexibility with goal-directed and coherent action control.* Accordingly, much of what was expressed in the present chapter is also relevant for selective and focussed attention tasks.

The question whether or not task elements can be integrated or should be kept separate depends on the available control parameters in the *combination* of subtasks. In general, when there is coherence or compatibility in the processes that have to be combined and difference or incompatibility in processes that should be kept separate, attentional performance will be enhanced. In contrast, when there is difference or incompatibility in the processes that have to be combined and coherence in processes that should be kept separate, mutual inhibition and cross talk interference will hamper performance.

In this connection, the broad concept of *similarity* represents an important factor determining the difficulty of coping with the specific dual-task requirements. Similarity refers to elementary relationships among subtask with reference to all possible task variables. A few prevailing examples of such similarity variables: semantic, syntactic, physical or grammatical similarities, similarities in color, form, orientation, movement, size, sound, mapping, timing aspects, body parts and sense organs, processing operations. Many of these examples can be further divided in more detailed aspects of similarity. Arithmetic operations, for example, can be divided further into addition, substraction, multiplication, etc.

Similarity was supposed to facilitate a combined or integrated performance of subtasks and thus to enhance task performance when it involves coherent *inputs* (e.g., stimulus locations, -configurations, -movements, -frequencies, -onsets) coherent *processing routines* (e.g., stimulus-response relations, timing mechanisms, cognitive operations), coherent *actions* (e.g., movement routines, frequencies, amplitudes, directions), or coherent *subtask goals*. This was termed *coherent similarity*. Coherence refers to common, related, corresponding, correlated, or supplementary subtask elements, of course in relation to the overall objectives of the dual task. Based on coherent similarity among subtasks, task elements can be combined or integrated. Therefore, coherence is a necessary condition

for skill integration. That is: based on the relationships among subtasks, individual single-task skills may be integrated into a common higher-order skill. The execution of such common higher-order skills will be much more efficient than the separate execution of lower-order routines. In specific, when skills have to be executed separately, there will always be difficulties related to selection, isolation, and coordination of (sub)goals and skills. For instance, different goals appropriate to the several subtasks do not have to be kept simultaneously active and coherent task performance will depend to a lesser degree on mutual inhibition of different and simultaneous activated brain programs. In conclusion, when subtask elements are characterized by coherent similarity, subjects may integrate them into one higher-order task, such that the limitations inherent to the organization of different processes are overcome. When it is possible to combine coherent subtasks, skill integration may thus become a significant determinant of skill acquisition, and thereby of dual-task performance.

Degrading effects of similarity were supposed to appear when subtask goals, processing routines, timing mechanisms or stimulus-response mapping between subtasks are different or unrelated. This was termed *incoherent similarity*. The selective activation of processing routines and actions will then become more critical. This means that processing operations always have to be directed to only one of the subtasks. With incoherent similarity, subjects may unintentionally combine the subtasks, which may lead to mutual disruption. In neurobiological terms, incoherent similarity may produce synchronized or correlated neural discharges on the basis of which the brain may combine representations that should be kept distinct. The erroneous combination of subtasks can be referred to as *cross talk*, *outcome conflict*, or *confusion*. When tasks are characterized by incoherent similarity, the extent of cross talk interference will depend further on the availability of other control parameters (e.g., elementary visual or phonological cues) enabling segregation of task elements. This was termed *consistent difference*.

With regard to training and skill development, the beneficial effects of 'automatization' should be understood as capacity enhancement on the basis of the acquisition of *special-purpose* brain programs. To be more precise: skill development can be understood as a gradual process of adapting and tuning neuronal networks to the (higher-order) consistencies among input processes, processing routines and response mechanisms. This means that performance becomes less dependent on inefficient *general-purpose* brain programs, that is, the neuronal networks with an abstract algorithmic character, covering a broader range of task processes. Special-purpose networks are smart, which means that they are specific and computationally efficient. In addition, they require lower degrees of activation in order to control behavior (inhibit competing programs) than general-purpose networks. In line with this, their execution may show lower metabolic activity, which may be experienced as effortless and subconscious. However, they also require very specific inputs in order to be triggered.

Special purpose programs will usually dominate over general-purpose programs for a given task when both cover the same task elements. However, when both are aimed at different *levels* of the same task or at different *tasks*, special-purpose and general-purpose brain programs can very well co-exist, i.e. steering and route planning in a driving task (different levels) or steering and calculating (different tasks).

By dual-task training, subjects can learn to benefit from coherent similarity or to handle incoherent similarity. Based on the relationships between coherent subtasks, individual single-task skills (or brain programs) may be associated and integrated into a common special-purpose skill of a higher-order. This new special-purpose skill capitalizes on the specific peculiarities of the overall task situation. Hence, the dual task will, to a certain degree, be performed as a single task. As opposed to single-task performance, only in dual-task performance, spreading or correlated activity among (to-be-integrated) brain programs may facilitate task performance. Therefore, such integrative learning can only take place with dual-task training. It can thus be predicted that beneficial effects of dual-task training will increase with the degree of coherent similarity among subtasks.

With reference to subtasks characterized by incoherent similarity, training may increase the specificity of skills. When skills are more specific, the chance that simultaneous actions will depend on the same brain programs will decrease. Because potential cross talk is avoided by decreasing 'neural overlap', interference effects in dual tasks, consisting of incoherent subtasks, will decrease with the specificity of subroutines. Training, which was supposed to increase the specificity of skills, may involve separate training of individual task components, or complete dual-task training. Accordingly, both single-task and dual-task training may strengthen the specificity of skills, and thereby enhance dual-task performance. As opposed to single-task training, however, only in dual-task training, interacting or correlated activity among (to-be-segregated) brain programs can be faced. The extent to which this is possible depends further on the availability of potential control parameters enabling segregation of task elements (consistent difference). Therefore, with substantial incoherent similarity, dual-task training will particularly be required to reach optimal skill segregation.

In conclusion, the value of dual-task training will increase with the degree to which dual tasks entail variables that enable the combination or segregation of subtasks, i.e., coherent or incoherent similarity or consistent difference. In order to ensure skill integration or segregation with dual-task training, the nature of similarity should be consistent over a period of time. Without consistent relationships between critical task variables (e.g., varied mapping) nothing can be learned. That is, the patterns of coincident neuronal activity will continuously change such that no smart wiring can develop that is tuned to the invariant properties of the task. It will be evident that, in case of (consistent) coherent similarities among subtasks, the development of skill integration will only appear with dual-task training and not with single-task training.

Different kinds of similarity may work out in a cumulative, or even multiplicative way. Spatial proximity, for example, will substantially aggravate the negative effects of superficial similarities of subtask elements. In contrast, spatial proximity may enhance the cooperative effects of coherent similarities. Accordingly, eventual effects of coherent and incoherent similarities always should be considered in combination.

The reviewed effects of similarity clearly show that interference effects are content-specific. This means that performance in dual tasks may be explained on the basis of a cognitive neuroscience framework as presented here, incorporating current knowledge concerning the functional and structural discontinuities in human information processing (in which networks of specialized attentional areas might play a role), and an analysis of the whole concrete task. The general principle of this orientation is that two operations performed simultaneously by the same or heavily interconnected structural systems will produce specific interference or interaction effects.

Of course, the variety of different aspects of similarity, including their interactions, and the numerous functional differentiated brain structures make it unlikely to provide simple rules enabling one to predict the effects of similarity for each task situation. Nevertheless, when searching for solutions, this should not tempt us only to look in the light (as suggested for example by Navon and Gopher, 1979; Wickens, 1984), while we know that most of it lies in the dark. Reality is complex, the brain is extremely complex, and the structure of human behavior will be accordingly complex.

Therefore, when making predictions with regard to multiple-task performance, knowledge concerning structural discontinuities in the brain and functional discontinuities in human behavior should be utilized. For example, the present section addressed processes such as goal orientation and behavioral flexibility, selective attention and divided attention, inhibition and cross talk, coherent and incoherent similarity, integration and segregation of processing operations, and the development of general-purpose and special-purpose brain programs. These kinds of processes all are related to *behavior adaptation and organization*, the selection, control and adaptation of processing operations in relation to the task requirements. These are well-known functions associated with parts of the prefrontal areas (see also § 5.3), though within the frontal lobe, dissociations between these functions have been identified (Fuster, 1989; Shallice, 1988). It is also known that practice renders performance relatively insensitive to frontal lobe damage (e.g., Luria and Tsvetkova, 1964; Walsh, 1978) and that prefrontal lobe damage severely hampers self-initiated activity (e.g., Milner, 1964), suppression of competing tendencies or irrelevant inputs (Fuster, 1980), and the inhibition and modification of well-learned routines (e.g. Luria, 1973; Perret, 1974). It should therefore be investigated whether these areas play a unique role with respect to the utilization of general-purpose brain programs and the generation of new special-purpose brain programs involved in the performance of untrained and complex tasks.

Chapter 5

Aging and multiple-task performance

5.1 Introduction

A substantial body of literature shows that older subjects are more penalized than young subjects in multiple-task situations[1]. The decrement in performance associated with the requirement to divide attention between concurrent tasks, relative to single-task performance, typically is found to be greater for older adults than for young adults (e.g., Broadbent and Gregory, 1965; McDowd, 1986; Ponds, Brouwer, and Van Wolffelaar, 1988; Talland 1962). The experimental literature reports one major hypothesis explaining increasing age-effects in complex tasks: the *slowing-complexity hypothesis*. Below, I will briefly describe this hypothesis and consider its strong and weak points. Next, on the basis of the general framework presented in Chapter 4, the directions in which this theory can be further developed will be proposed. In this connection, also the new experimental data and conclusions, provided by the experiments of the present thesis, will be outlined.

5.2 Slowing and complexity in dual tasks

The slowing-complexity hypothesis is partly based on a large number of studies, documenting that older subjects are slower than their younger counterparts in almost all behavioral domains so far investigated (for reviews, see: Birren, Woods, and Williams, 1980; Korteling, 1988; Welford, 1977a; Salthouse, 1982, 1985a, 1985b). This *generalized slowing* (Birren, 1974) usually is regarded as a reflection of structural changes in the central nervous system, that is: cell death, metabolic changes and reduced blood supply. Peripheral processes seem less affected. Central degenerative processes may cause reductions in the strength of neuronal signals or the velocity of neuronal conduction, increases in random background activity, and persistence of earlier activations of neurons, thereby producing a lowered effective ratio of signal to noise (e.g., Welford, 1977a/b). This supposed lowered signal/noise ratio requires the system to integrate more information in order to reach the same degree of confidence

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[1] As was argued in Chapter 1, it is impossible to provide a completely satisfying definition for *old age*. Therefore, aging is conceived as a compound statistical phenomenon related to chronological age in adulthood, becoming sufficiently powerful for behavioral applications by about 60 years of age or older.

(e.g., Crossman and Szafran, 1956; Gregory, 1957; Welford, 1958, 1981). Regardless of the factors determining decreased neuronal processing speed, Salthouse (1985a) has argued that this mechanism may explain a wide variety of phenomena, ranging from differences in elementary reaction time tasks to strategical differences in nonspeeded tasks, such as problem solving tasks. This position is supported by studies demonstrating that much of age-related differences disappear when differences in speed are statistically controlled (e.g., Hertzog, 1989; Schaie, 1989).

Many of the studies on age-related performance differences have demonstrated that age-effects increase with task complexity (e.g., Birren, 1965, 1974; Cohen, 1979; Gaylord and Marsh, 1975; Griew, 1964; for reviews, see Salthouse 1985a; Welford, 1977a). Complex tasks, involving elaborate 'central' processing of information (e.g., spatial transpositions or symbolic manipulations), typically show greater age effects than 'peripheral' tasks, which have a more simple and straightforward stimulus-response structure (e.g., Cerella, 1985; Cerella, Poon, and Williams, 1980). In line with this, it has been found that visual search under varied mapping conditions (see § 3.3.1) is more vulnerable to age-related decline than search under constant mapping conditions (e.g., Madden and Nebes, 1980; Plude and Hoyer, 1981).

These findings have been elaborated with the notion that cumulative slowing in successive processing steps causes performance differences between age groups to increase with the number of required processing operations (Cerella et al., 1980; Hale, Myerson, and Wagstaff, 1987; Myerson, Hale, Wagstaff, Poon, and Smith, 1990). Based on meta-analyses of data collapsed across studies in which reaction time (RT) performance of young adults was plotted against that of older adults for different speeded tasks, Cerella (1985) and Cerella et al. (1980) found a linear relationship. Hale et al. (1986) and Myerson et al. (1990) even found an exponential relationship. Slopes typically range between about 1.2 and 2.0. These studies indicated that speeded performance of the old subjects can be predicted on the basis of younger subjects' performance, without regard to the kind of task used. Therefore, task complexity, as indicated by the young subjects' performance, may be conceived as a parsimonious and overall predictor of aging-related performance differences.

Salthouse (1982, 1985a) suggested that a dual task is nothing more than a complex version of a single task, which necessitates the involvement of more processing operations in the same amount of time. According to this view, dual tasks represent just one of several ways to increase overall task complexity (McDowd and Craik, 1988; Salthouse, 1982, 1985a; Salthouse, Rogan, and Prill, 1984; Somberg and Salthouse, 1982). This would mean that observed age effects of complex single tasks and dual tasks are the same. Accordingly, the substantial age-related performance differences in dual tasks are caused by the mere complexity of these tasks, and nothing else. This notion has mostly been referred to as the *complexity effect* or the *complexity hypothesis* (e.g., Madden, 1990). Note that the complexity effect often is

viewed as an immediate consequence of generalized slowing (e.g., Salthouse, 1982, 1985a). In that case, the more unifying *slowing-complexity* expression may be preferred as a label for an overall explanation for increasing age effects in dual-task situations. The reasoning leading to this hypothesis can be summarized as follows: on the basis of cumulative effects of generalized slowing, caused by structural changes in the nervous system, aging-related performance deteriorations increase with task complexity, that is the number of required processing operations.

The complexity effect has been tested by McDowd and Craik (1988). In two experiments, McDowd and Craik (1988) tested the hypothesis that age differences in dual-task performance are amplified by an increase in the complexity of the constituent tasks. Although they found highly reliable age decrements in divided attention performance, in terms of both relative and absolute divided attention costs, the magnitude of age differences was not consistently affected by complexity manipulations. McDowd and Craik (1988) also tested the complexity hypothesis by plotting reaction-time performance of the young subjects against that of the old subjects for various task conditions. It appeared that in their study, reaction time performance of the old subjects could be predicted on the basis of younger subjects' performance, without regard to the nature of the task. This led the authors to conclude that the requirement to perform two tasks concurrently did not differ qualitatively from other ways of increasing overall task complexity.

Recently, it has become popular to 'explain' age differences in any aspect of cognition by an aging-related reduction in processing resources (or a similar construct, Craik, 1977; Craik and Simon, 1980; Crossley and Hiscock, 1992; Hasher and Sacks, 1979; Kausler, 1982; Wright, 1981, see Salthouse, 1988a for about 40 references since 1980). However, as we have seen in the previous chapter, such circular explanations, do not provide insight into the underlying mechanisms determining aging-related perform-ance deteriorations. That is, the existence of age differences in task performance cannot be nontrivially explained by a reduction in processing resources or capacities, when the reduction in these faculties is inferred on the basis of age differences in task performance (Salthouse, 1988a). This objection also involves the so-called *processing rate theory*, in which the factor 'time' is regarded as the main processing resource responsible for age effects (Salthouse, 1985a). This theory recently has been incorporated into a more elaborate theoretical perspective on cognitive aging (Salthouse, 1988a, 1988b) in which the concept of processing resources is divided into different subfaculties, i.e., limitations in time (speed of information processing), space (working memory), and energy (mental energy or effort). For that matter, it should be noted that Salthouse (1988a) is well-aware of the vacuous and circular nature of the resource construct (see Chapter 3, Navon, 1984; Neisser, 1976; Neumann, 1987).

Since everyday life provides us with many examples in which the older are slower than the younger, the use of generalized slowing for explaining age-effects in (complex) dual tasks seems to be intuitively appealing. However, although the idea of generalized slowing is based on structural changes in the nervous system, it is not very well specified why and how this leads to behavioral slowing. According to Birren et al. (1980), a difficulty with the signal/noise explanation is that there is no obvious neural locus or mechanism that would increase the noise level of the older system. Similarly, there is no circumscribed mechanism explaining how neuronal changes lead to slowed information processing. Also experimental evidence is equivocal (Salthouse, 1985a). Birren (1970) supposes that the slowing phenomenon can be attributable to reduced levels of activation or arousal, which is mediated by subcortical structures, like the ascending reticular system, with diffuse connections throughout the whole nervous system. This is supported by reduced cell counts in the locus coeruleus, reported by Brody (1976) and Brody and Vijayashankar (1977).

Although processing speed conceptions rely on degenerative processes in the nervous system, theorists have not provided a generally accepted underlying mechanism that can explain precisely *how* neuronal degeneration causes generalized slowing. Actually the theory tends to neglect immediate consequences of one of the most pronounced basic facts of aging: a location-specific decrease of neuronal connections accompanied with hypertrophic changes in neuroglia and decreasing plasticity. With increasing age, the number of cortical axon and denditric terminals decreases ultimately leading to the loss of entire neurons (e.g., for reviews see Bondareff, 1975; Brody and Vijayashankar, 1977; but see Cragg, 1975). According to Bondareff (1979), the loss of synapses is not a secondary consequence of loss of entire neurons. The older neurons need not be lost in order to influence function. This means that the loss of neuronal connectivity can be regarded a major candidate for aging-related behavioral phenomena. In the previous chapter, the high degree of (smart) neuronal connectivity was invoked as the basis of the high processing power and plasticity of the nervous system. Therefore, starting with this framework, it may be explained how neuronal decrease may lead to the various behavioral deteriorations with aging. This will be done in the next paragraph.

Furthermore, it is obvious that the brain cannot be dealt with as a uniform organ. The decline of neuronal connections does not occur generally, but concerns only selective parts of the brain. These differences must be taken into account in explaining variations in structure and function with increasing age in adulthood. With age, total brain mass shrinks 10-15% in the normal aged (Wisniewski and Terry, 1976). Of the structures studied, the hippocampus and the neocortex (prefrontal and superior temporal areas) appear the most affected (Brody, 1973; Brody and Vijayashankar, 1977; Critchley, 1942; Haugh, 1985; Scheibel and Scheibel, 1975; Tomlinson and Henderson, 1976). Other brain areas, associated with other functions,

(e.g., inferior temporal gyrus and inferior olivary nucleus) show little or no degeneration with increasing age (Brody, 1973; Brody and Vijayashankar, 1977). Generalized-slowing conceptions generally do not take in account the specificity of these neural changes with aging.

Of the most affected areas, the prefrontal areas are associated with *behavior adaptation and organization*, that is self-initiated programming, monitoring, and modification of behavior such that it becomes appropriate to the peculiarities of various situations (e.g., Fuster, 1980; Luria, 1973; Petrides and Milner, 1982). The hippocampus is particularly associated with long-term memory functions, i.e., *plasticity* and the *functional consolidation of adaptations*. This means that affected areas are related to behavioral organization, adaptation and plasticity. The relatively great neural losses in the prefrontal areas and in the hippocampus also reflect a global distinction that can be made between abilities that are relatively sensitive to the effects of aging and abilities that are less sensitive or 'age-irrelevant'. Age-irrelevant tests generally involve familiar and overlearned skills, such as verbal and lexical abilities that do not require active, internally generated processes, whereas age-sensitive tests involve long-term memory functions (as opposed to immediate memory) and the self-initiated manipulation of unfamiliar materials (e.g., Botwinick, 1977; Clark and Knowles, 1973; Cornelius, 1984; Craik, 1986; Craik and Bosman, 1992; Deelman, 1993; Denney, 1982). In this connection, it is important to note that, whereas extensive practice does have substantial effects on perceptual, cognitive, and motor performance (e.g., Gibson, 1953; Salthouse and Somberg, 1981), few studies have evaluated the performances of older adults on previously acquired skills or over extended series of sessions. The general picture, provided by these studies is that initial age differences do not change with extended practice (for reviews see Kausler, 1982; Salthouse, 1985b) and that these differences are predominately found with respect to *new* or *unfamiliar* skills—i.e., skills that were not acquired (as 'automatic' skills) before old age (for a review see Fisk and Rogers, 1991).

To summarize, a complete explanatory framework for aging-related decline in dual-task situations still is far away. In order to gain more insight into the underlying mechanisms determining age effects in multiple-task situations, we should start with the specific and general characteristics of the aging brain in combination with the dual-task variables producing special problems for older subjects. With the aid of the cognitive neuroscience framework presented in the previous chapter, it may be possible to formulate the basic principles for such a theory.

5.3 Determinants of age effects in multiple-task performance

As has been noted before, single-task training produces little transfer to dual-task performance (e.g., Schneider and Detweiler, 1988), whereas dual-task skills can, in a limited way, transfer between different dual-task combinations (Damos and Wickens, 1980). In other words: dual-task performance seems, at least partly, to be determined by a 'dual-task ability'. Furthermore, the abundance of studies documenting relatively large age-effects in dual-task situations suggests that these abilities deteriorate with increasing age.

With reference to the possibility that individuals initially differ in general time-sharing ability a word of caution seems appropriate. According to Wickens, Mountford, and Schreiner (1981), this idea can be substantiated by obtaining high correlations between performance scores in qualitatively different dual-task situations and lower correlations between single tasks or between single- and dual tasks. Wickens et al. (1981) examined individual differences in time-sharing ability of 40 practiced subjects in nine pairwise combinations, made up of four single tasks: manual tracking, auditory short-term memory, digit classification, and visual line judgement. A factor analysis of single- and dual-task scores yielded only factors that were specific for task characteristics with no evidence of a factor loading exclusively on dual-task scores. Also on the basis of a factor analysis of single- and dual-task scores, the a similar conclusion was drawn by Fogarty and Stankov (1982). Other authors who also studied differences between individuals in a general time-sharing ability question the assumption that time-sharing ability can be identified as a distinct trait. (e.g., Braune and Wickens, 1986; Brookings, 1987; Jennings and Chiles, 1977). On the basis of the results of these kinds of studies, Davies, Jones, and Taylor (1984) conclude that the evidence supporting the notion of a general time-sharing ability is not particularly strong. All these studies have been carried out with normal populations. How this conclusion relates to age-differences has not been investigated yet.

Although it may be taken for granted that neuronal decrease is fundamentally related to the problems of older subjects in task performance, it is not clear *why* and *how* these processes lead to difficulties in dual-task situations. Accordingly, the supposed intervening variables are unknown. In § 5.2 it was acknowledged that aging is associated with specific losses in neuronal connectivity. According to the cognitive neuroscience framework presented in the previous chapter, the high degree of associative neuronal connectivity forms the basis for the high processing power of the brain and for the underlying mechanisms regarding the nature of capacity limitations in multiple-task performance. In addition, decreased neuronal connectivity, as found in prefrontal and medial temporal areas, may be directly relevant for multiple-task performance because it may affect various functions, which can be united under the

term *behavior organization and adaptation*. As was argued in § 4.6, behavior organization in dual-task performance involves *active* processes such as performance integration on the basis of coherent similarity, or, performance strategies such as skill segregation in case tasks are characterized by incoherent similarity. Therefore, various arguments can be given for the importance of decreased neuronal connectivity with reference to age-related differences in multiple-task performance.

As was claimed in § 4.2, decreasing connectivity should not be identified with forgetting or decay of skills. Reduction in synaptic strength probably is also an indispensable component of learning and plasticity, i.e., skill and knowledge acquisition (Churchland and Sejnowski, 1992). Learning by neuronal degradation may be based on the principle of *functional validation*, i.e., only those connections whose functional characteristics are appropriate to the organism's environment will survive. In addition learning may involve, *functional specification* of nonspecified, multi-potential neurons. This is the formation of selective response properties in response to the environmental input (Hirsch and Jacobson, 1975; Pettigrew, Olson, and Barlow, 1973). Both supposed learning processes probably involve the development of a more specific and goal-oriented and a less redundant and plastic neural organization. When the superfluous neuronal connectivity decreases when people grow older, the potential for associative information processing and learning probably will decrease. This may reduce a subject's potential to detect and utilize new combinations, invariances, and covariations with regard to inputs, processing operations, or actions, and modify neuronal circuitry accordingly. In other words—and in line with the final suggestion of § 4.6—it can thus be hypothesized that older subjects may be hampered in the utilization of multi-potential brain programs in unfamiliar situations and the modification or generation of special-purpose brain programs to ultimately cope effectively with these situations. Hence, they may be expected to hang more on existing processing routines.

Special-purpose brain programs may be assumed to have a more simple structure than general-purpose programs. Therefore, the fact that especially the cortical 'behavior organization and adaptation' areas show shrinkage with increasing age in adulthood indicates that neural decline with aging in adulthood may be (partly) an *inherent consequence of learning and experience*, rather than an exclusively endogenous process of neural degeneration.

When neural associative potentials decrease, the integration of many elementary brain programs into fewer higher-order programs will be more difficult to accomplish. In that case, a coherent dual task may remain to be performed as two different tasks, instead of being performed more like one integral task. In contrast, when the subtasks of a dual task are incoherent, such that the subtasks have to be kept apart, decreased neuronal connectivity may hamper the purposive mutual inhibition of activated channels or processing structures, such that information processing would show more

cross-talk among channels and task performance will become more susceptible to mutual intrusions. Cortical cell loss in old age may deplete the individual's potential for selective inhibition, such that different brain loci effectively, or functionally, become closer to each other (e.g., Kinsbourne and Hicks, 1978).

Decreased neuronal connectivity may also explain the substantial evidence of an age deficit in selective attention (e.g., Hasher and Zacks, 1979, Hoyer and Plude, 1980). The relevant studies indicate that older adults have more difficulty than young adults in allocating attention exclusively to task-relevant material in e.g., visual search (e.g., Rabbit, 1965) or embedded figures (e.g., Basowitz and Gorchin, 1957). In a review of the literature, Plude and Hoyer (1985) conclude that aging-related selective attention problems typically occur in divided attention situations, that is, when there is no advanced knowledge of where to direct attention. When searching or discriminating relevant information, the brain has to operate very selectively. That is, it has to facilitate relevant programs and inhibit irrelevant programs, for example by altering the polarization level of dendrites. Neuronal leakage may interfere with this process, especially when prior information concerning the localization of relevant information is lacking and irrelevant inputs thus may intrude during search activity. This may especially be so when these irrelevant inputs activate dominant routines. Experiments on Stroop color-naming (focussed attention) show that the magnitude of competition effects produced by incompatible dominant word information has been found to increase with adult age (Cohn, Dustman, and Bradford, 1984; Comalli, Wapner, and Werner, 1962; Hahn, Hoyer, and Silverstein, 1980, but see Rogers and Fisk, 1991).

Finally, declining neuronal connectivity is compatible with general age-related behavioral slowing found in most laboratory experiments, the effects of which increase with task complexity. Only in very elementary tasks or in more complex (familiar) tasks for which the special-purpose circuitry already was developed before old age, age effects may be absent. When an efficient geometric organization of smart mechanisms cannot be utilized or ensued, information processing remains more dependent on overall and less effective general-purpose brain programs. The operation of these kinds of programs generally will cost more time, particularly when a task becomes more complex. Such processes may also be imitated by computer-simulated neuronal networks (e.g., Hopfield and Tank, 1986).

The arguments presented above indicate that decreased neuronal *connectivity and plasticity* may be a more applicable, and from a neurobiological point of view better founded, basis for an explanation than increased neuronal noise. Decreased neuronal redundancy may produce a reduced potential to utilize general-purpose brain programs, to modify or form simple-structured special-purpose programs (and thus to learn from experience), to incorporate coherent similarities and to segregate incoherent similarities, to suppress the activation of irrelevant (dominant) routines,

and process information quickly. Of course the effects of these difficulties will increase with task complexity, or the required number of elementary operations.

Apart from decreased neuronal connectivity, several other metabolic changes with increasing age may also be relevant for an explanation of aging-related performance effects. The general hypertrophic changes in neuroglia with age—decreasing neuronal-glial ratio and larger glial cells (e.g., Hansen, Armstrong, and Terry, 1987; Landfield, 1982; Lindsay et al., 1979) are particularly interesting. It has been shown that environmental enrichment increases all neuronal measures of enhanced cell activity, together with an increase in the number of glial cells (Altman and Das, 1964; Diamond et. al., 1985). In addition, the brain of Albert Einstein tended to *lower* neural-glial ratios than the brains of 11 control brains (Diamond et. al, 1985). According to Phelps (1991), astrocytes are highly plastic themselves and have the metabolic capacities to influence the plasticity and function of neurons. In conclusion, neuroglial cells play a more complex role in central nervous function than was previously recognized. The question how the glial growth in old age relates to the functional phenomena demonstrated by older persons, is still far from a satisfying answer.

5.4 The experimental questions

Based on the previous cognitive neuroscience orientation, it may be presumed that the parsimonious slowing-complexity hypothesis does not explain everything. Of course, a dual task is more complex than a single task and thus may magnify age-related effects in single-task performance. This, however, does not deny the possibility that dual tasks in many cases may contain characteristics that are especially difficult for older people. This is not because of their slower information processing speed or because two more than one, but because of higher-order relationships that emerge from the combination of subtasks and that require the execution of particular processing operations that become more difficult with increasing age. These operations globally can be grasped in terms of the integration and segregation of brain programs, as determined by coherent and incoherent similarity and the flexible adapation of brain programs. These phenomena would follow directly from neuronal connectivity and plasticity decline in adulthood. Decreasing neuronal connectivity, for example, may prevent the integration, linking, or combination of coherent information from multiple sources. Alternatively, it may hamper the mutual inhibition of activated channels or processing structures, such that task performance would show more effects of leakage and cross-talk in information processing.

In this context, the experiments described in the present thesis were focussed on *the identification of problems that older subjects may have with task variables that are specific for dual tasks and thereby gaining more insight into underlying mechanisms that determine the magnitude of age-effects in multiple-task situations.*

Because of its general implications, the data of the present thesis were always evaluated on compatibility with the slowing-complexity hypothesis, or with the idea of generalized slowing as the most universal phenomenon of functional decline with increasing age. In some instances the slowing-complexity hypothesis, and the generalized slowing phenomenon, will appear less general than should be expected. Apart from some slight modifications, the contents of the chapters in this thesis are the same as those of the corresponding manuscripts already published as journal articles.

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Chapter 6

Perception-response speed and driving capabilities of brain-damaged and older drivers

6.1 Introduction

One of the most pronounced residual effects of brain injury is general psychomotor slowing (e.g., van Zomeren and van der Burg, 1985). Reaction time (RT) tasks in particular appear to be sensitive to the long-lasting consequences of diffuse and focal brain damage (e.g., Miller, 1970; Norrman and Svahn, 1961; Stokx and Gaillard, 1986; van Zomeren and Deelman, 1976). General behavioral slowing is observed in older people as well. Whenever psychomotor speed has been compared in adult groups differing in age, older individuals are slower than younger ones (e.g., Birren, Woods, and Williams, 1980; Cerella, 1985; Hale, Myerson, and Wagstaff, 1987; Salthouse, 1985; Welford, 1958, 1965).

Despite the evident differences in the neural etiology of age-related and brain damage-related slowing, behavioral consequences in both groups seem to be similar (Talland, 1965; Benton, 1977). In situations such as driving an automobile, both older and brain-damaged people may act too slowly in coping with task demands. For older drivers, this idea was substantiated by van Wolffelaar, Rothengatter and Brouwer (in press), who found that older drivers needed 50% more time than young drivers to observe and decide whether they could safely merge into the traffic on a road. In terms of signal detection sensitivity, the accuracy of merging decisions was the same for both age groups. With respect to trauma patients, Stokx and Gaillard (1986) found that decreased response speed in patients with diffuse traumatic brain injury was related to slower performance in a number of driving tasks. They concluded, therefore, that laboratory tasks may have diagnostic value with respect to elements of driving. Sivak, Olson, Kewman, Hosik, and Henson (1981) also concluded that driving problems exhibited by brain-damaged subjects partly result from perceptual and cognitive deficiencies, which may be diagnosed by (neuro)psychological tests, such as RT tests.

However, the development of diagnostic measures that might be used to find driving-related problems requires a better understanding of the task variables that

impose special problems for brain-damaged patients and/or older subjects. Therefore, similarities and differences in laboratory RT performance of both groups relative to normal subjects are of particular interest. In addition, the generality of these data with respect to actual driving should be verified.

For this purpose three experiments—a laboratory study, a field study and a combined laboratory-field study—were carried out with manipulation of task variables, that are likely to affect performance of brain-damaged patients or older subjects in practical situations. The first study addressed the hypothesis that choice RTs of older and brain-damaged subjects may show more interference effects between subsequent stimuli as a consequence of persistent neural noise. Therefore, two task variables were manipulated which were expected to affect sequential effects of stimuli in a choice RT task.

In the second study a choice RT task based on time estimation, was used in the laboratory as well as during car driving. This experiment was undertaken to assess group differences in the capability to estimate time, which may be critical in many traffic situations, and to obtain more insight into the causes of eventual differences between performance on elementary laboratory RT tasks and actual driving performance.

The third study was aimed at performance differences in a driving task that could be regarded as critical with respect to perception-response speed and in which task load was varied. Finally, the predictive value of the laboratory tasks for this driving task was determined.

6.2 Experiment 1: Discrete choice RT

One of the most-discussed hypotheses for age-related slowing is the idea that with increasing age the central nervous system shows either a reduction in signal strength or an increase in random background activity. Numerous variations of this concept have been proposed (e.g., Birren, 1970; Crossman and Szafran, 1956; Layton, 1975; Rabbit, 1980; Welford, 1958, 1965, 1977a, 1977b, 1981, 1984), all of which state that a variety of factors—such as diffuse cell loss, metabolic changes, or decreased cerebral blood supply—cause the effective signal-to-noise ratio in the brain to decrease. Because this lower ratio requires a greater number of information samples to reach the same criterion certainty, it generally produces slower rates of information processing. Apart from cell loss, brain damage also may cause a variety of changes in neural metabolism and blood supply. Therefore, brain damage also may decrease the neural signal-to-noise ratio and consequently slow psychomotor speed. It is not easy to test the signal-to-noise hypothesis directly, and to the extent this is done the results do not consistently support the hypothesis (Salthouse, 1980; Salthouse and Lichty, 1985).

One of the many variants of the signal-to-noise hypothesis states that age-related behavioral slowing may be explained by noisy and residual neural activity that increases in duration and strength with age (Axelrod, 1963; Welford, 1965, 1977b). When the interval between the execution of a response and the arrival of the next stimulus (the *response-stimulus interval*, RSI) is long, residual activity has time to dissipate and thus will not affect response speed. However, with short RSIs this activity would impair perception-response speed when a stimulus is different from the one immediately preceding it. Otherwise, when successive stimuli are the same, information processing is usually less affected or may even be facilitated (the *repetition effect*; see Kirby, 1980; Rabbitt and Vyas, 1980). Repetition effects are usually found with short RSIs (about 0.5 s or less), when the delay between successive stimuli should not be greater than the residual neural activation. Alternation effects—that is, shorter RTs when a stimulus differs from the preceding one—are mostly found when RSIs or inter-stimulus intervals are long, which means that these effects can not be explained in terms of residual activation (Fozard, Thomas, and Waugh, 1976; Waugh, Fozard, Talland, and Erwin, 1973).

Based on the foregoing conceptualization, we predicted that differences between the experimental groups and the control subjects would increase with shortening of the RSI and with increasing difference between subsequent stimuli. Usually the magnitude of repetition effects increases with decreasing compatibility between stimuli and responses (Kirby, 1980). Therefore, the experimental RT task involved a varied sequence of compound stimuli with an unstraightforward mapping to responses.

6.2.1 Subjects

A total of 30 male subjects, divided into three groups of ten, participated in the experiment. The brain injury group included patients who had recovered from the effects of diffuse brain injury caused by a trauma. Their mean age was 30 (range 21-43). All patients had been in a coma two to nine years earlier, for a mean duration of 16 days (range 5-35 days). Patients were screened by a revalidation physician of the cooperating revalidation center. According to existing medical criteria, none of the patients used medications or showed deficits that interfere with normal psychomotor or cognitive functioning.

Ten older male subjects with a mean age of 66 years (range 61-73 years), and ten male control subjects with a mean age of 30 years (range 21-43 years) were chosen such that their educational levels and driving kilometrage over the last three years were matched to those of the brain-damaged subjects. None of the subjects had a history of cardiovascular disease, and all were currently healthy and had normal or corrected-to-normal visual acuity (Landolt-C test). None of the subjects used narcotics or tranquil-lizers. The control and older subject group had normal age-corrected scores on Fluency I and II, two verbal speed subtests of the Groninger Intelligence Test (Snijders and

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Verhage, 1962). As expected, the patient group showed substantially lower scores on this test.

6.2.2 Method

Subjects were seated in a sound-attenuated room in front of a stimulus display (Fig. 6.1), which contained four stimulus lights, two response buttons, and a neutral button that was not used in this experiment. A compound stimulus consisted of the simultaneous presentation of two lights: one of the colored lights and either the left or right white light. This allowed four compound stimuli, which were presented equally often. Subsequent compound stimuli could be the same (four sequence alternatives), differ by one of the two lights (eight alternatives), or be completely different (four alternatives).
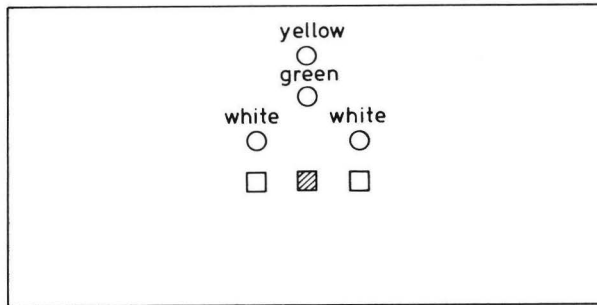

Fig. 6.1 Configuration of the stimulus display for the choice reaction task (round = lights, square = response buttons, hatched = neutral button).

Compound stimuli as well as RSI (100, 500 and 1250 ms) were randomly combined and presented. Because all compound stimuli were equiprobable and sequentially balanced, stimulus sequences could be divided into four similarity categories consisting of four alternatives: 0% difference, 50% difference by a white light change, 50% difference by a colored light change, and 100% difference.

The stimuli were presented in two blocks of 145 each in which the RT on the first stimulus was not recorded. Subjects were instructed to press the left or right button as quickly as possible, keeping their left and right index fingers on the respective response buttons. Two compound stimuli (green-left and yellow-right) mapped to the left button and the other two mapped to the right one. After five blocks of 50 practice trials, all subjects kept error rates below 5%. Feedback on incorrect responses was given by a 1000-Hz tone. Experimental control and data acquisition were governed by a PDP 11-03 computer.

6.2.3 Results

Error rates of the three groups varied between 3.1% and 3.6%, which was not statistically different. A 3 (Groups) × 3 (RSI) × 4 (Sequence) ANOVA on the RTs, with subjects nested under groups, showed a main group effect $F(2,27) = 10.2$, $p<0.001$. Both the older subjects and the patients were significantly slower than the controls. Separate analyses showed that the patients' RTs, which were approximately halfway between those of the older subjects and the controls, did not differ significantly from RTs of the older subjects. RT increased monotonically with difference in the sequence, $F(3,81) = 203.0$, $p<0.0001$. Fig. 6.2, in which the mean RTs of the two 50% difference categories are collapsed, shows that the strength of this effect was unequal for the three groups, being largest for the older group, $F(6,81) = 3.7$, $p<0.005$.
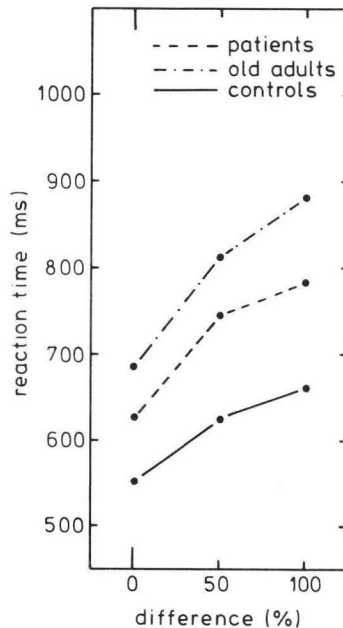

Fig. 6.2 Mean RTs of the three groups as a function of the difference (%) with the immediately preceding stimulus combination. The two 50% difference categories are collapsed.

Separate analyses indicated that the difference between the older group and the controls with respect to this interaction was significant, $F(3,15) = 6.13$, $p < 0.01$, whereas the difference between the controls and the patients just failed to reach significance, $F(3,15) = 2.87$, $p = 0.07$.

For RSIs of 100, 500 and 1250 ms, mean RTs were 723, 698 and 713 ms, respectively, $F(2,54) = 10.2$, $p < 0.005$. There was no significant interaction between RSI and Groups, which indicated that group differences did not increase with decreasing RSI. A significant interaction between RSI and stimulus sequence, $F(6,162) = 18.9$, $p < 0.0001$, indicated that interfering aftereffects of alternating stimuli decreased significantly with increasing RSI. As can be seen in Fig. 6.3, the repetition effect did not change to an alternation effect with increasing RSI. This may be explained by the low degree of stimulus-response compatibility. Although the effect of stimulus difference tended to collapse sooner (in terms of RSI) for the controls than for the experimental groups, the Group × Sequence × RSI interaction was not significant.

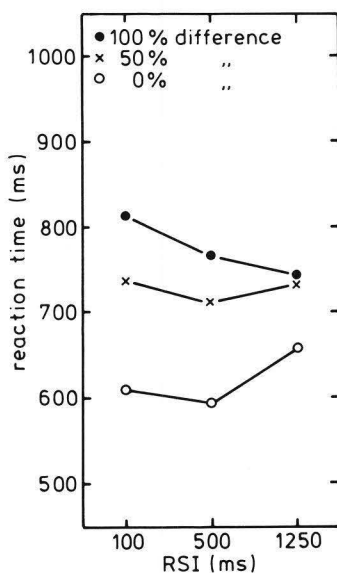**Fig. 6.3** Mean RTs affected by difference from the prior stimulus as a affected by the response-stimulus interval (RSI). The two 50% difference categories are collapsed.

6.2.4 Conclusions

The older subjects and, to a lesser degree, the patients were significantly slower than the controls. Increasing RTs with sequential alternations showed a clear repetition effect. This effect of stimulus sequence was stronger for the older

subjects and, to a minor degree, the patients than for the controls. In addition, the magnitude of the repetition effect increased with decreasing RSI. These findings are consistent with the results of previous work on reaction time in relation to RSI and sequential effects and with the conception that residual neural activity may interfere with information processing when subsequent stimuli are different. The interaction suggests that the magnitude of this residual activity is larger for the experimental groups. However, effects of RSI on reaction times or on repetition effects were not different for the three groups, which is inconsistent with the neural noise hypothesis.

In conclusion: the data show that test sensitivity for behavioral slowing of older or brain-damaged subjects can be increased when RT scores are based on responses on dissimilar stimulus sequences, provided that RSIs are short and stimulus-response compatibility is low. On a theoretical level, only the sequence data (not the RSI data) support the hypothesis that the magnitude of interfering neural aftereffects increases with brain damage or with age.

6.3 Experiment 2: Time categorization

There is a growing interest in the relation between performance on psychomotor tasks and on driving tasks for older subjects (e.g., Panek, Barrett, Sterns, and Alexander, 1977; Ponds, Brouwer, and van Wolffelaar, 1988) and for brain-damaged subjects as well (e.g., Sivak et al., 1981; Stokx and Gaillard, 1986). Correlations between laboratory and driving performance, however, are not always impressive (van Wolffelaar, van Zomeren, Brouwer, and Rothengatter, 1988). This may be ascribed to psychomotor differences between (simple) laboratory tasks and car driving. Driving may be regarded as a complex dual-task requiring manual as well as foot responses based on a dynamic visual scene consisting of multiple stimuli—in varying degrees of discreteness.

With these differences in mind, the second experiment was undertaken to discover how RT performance of the three groups changes under conditions with varying degrees of similarity to actual driving. Most RT tasks are based on discrete and unambiguous stimuli. However, when driving a car, a person usually has to respond to more continuous variables, such as speed and distance. Time is also an important—often, the most critical—variable that must be estimated quickly and accurately in order to make appropriate decisions (e.g., time to collision or times of yellow traffic signals; see van der Horst, 1990). Therefore, for the present experiment an RT task was chosen involving quick and accurate responses based on time estimations.

6.3.1 Method

Experiment 2 was carried out with the same subjects as those in Experiment 1. Subjects performed an RT task in one laboratory condition and two field conditions. In the laboratory condition, the same stimulus-response display and sound-attenuated room as in Experiment 1 were used; the white lights of this display were not used, however. In the two field conditions, the experimental task was performed in a stationary instrumented car and when this car was driven at 20-25 km/h on a path free of other traffic.

In the laboratory condition, a trial started when the green light of the display (Fig. 6.1) was turned on for a duration varying between 750 ms and 5250 ms. When the green light was turned off, the yellow light was turned on. At that moment the subject pressed one of the two buttons as quickly as possible with the index finger of his preferred hand. If the green light had been on for fewer than 3000 ms, the subject had to press the left button; in the other case he was to press the right one. When the subject was not responding, his finger remained on the neutral button. Duration of the green light presentation was randomly chosen from 10 intervals differing in steps of 500 ms (750, 1250, 1750 ... 5250 ms). This means that the two most difficult ones to estimate were 2750 and 3250 ms because they were closest to the 3000 ms decision margin.

In the field conditions, the stimulus lights were mounted on the car hood in the line of sight such that visual angles were equal to those in the laboratory conditions. Pressing the brake or gas pedal with the right foot replaced responding left (< 3000-ms intervals) or right (> 3000-ms intervals) with the index finger in the laboratory condition. Between trials the right foot remained on the gas pedal. Effects of these motor response variations were reflected by performance differences between the laboratory and the stationary car condition. In the driving condition subjects had to perform the aforementioned time-categorization task together with steering and controlling speed on a path free of other traffic. Performance differences between the stationary and driving condition represent the extra motor response and attentional demands specific to driving as a complex dual-task. The curves in the path were marked by two parallel lines 2.5 m apart. In order to minimize trade-off differences between the driving task and the reaction-time task, subjects were requested not to cross these lines and to maintain driving speed between 20 and 25 km/h.

All three task conditions consisted of 80 trials. Response-stimulus interval (RSI) was fixed at 3.5 s. Feedback on incorrect or too slow (> 2 s) responses was given by a 1000-Hz tone. For practical reasons the laboratory conditions always preceded the field conditions, with a one-hour rest period between. The order of field conditions was counterbalanced across subjects. In all conditions, subjects

were instructed to keep their error rate below 15%. After two practice blocks of 60 trials most subjects were able to reach this level.

6.3.2 Results

In order to avoid unpleasant accelerations in the driving condition, the gas pedal responses had to be made with some care. This, together with the fact that the gas pedal replaced the neutral button of the laboratory conditions, made suspect the validity of the RTs on the five time intervals longer than 3000 ms. Therefore a 3 (Groups) × 3 (Conditions) × 5 (Time Intervals < 3000 ms) ANOVA was carried out on the brake RTs of the correct responses, and a similar log-linear analysis on all time intervals was carried out on the error percentages (Bishop, Fienberg, and Holland, 1975). In all analyses, subjects were nested under groups.

Fig. 6.4 shows the group results collapsed over time intervals. Both the older subjects and the patients responded slower than did the controls, $F(2,27) = 7.42$, $p < 0.005$. In contrast to the previous experiment, the patients tended to be slower than the older subjects. Separate analyses indicated, however, that this difference was not significant. RTs increased from laboratory to driving conditions, $F(2,54) = 30.0$, $p < 0.0001$.
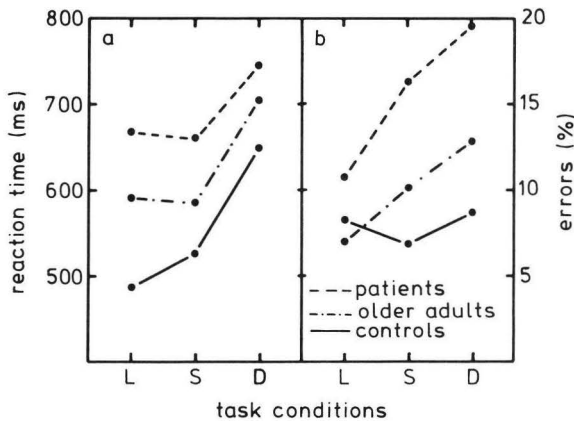
Fig. 6.4 Mean RTs of the correct responses **(a)** and error percentages **(b)** of the subjects in three conditions of the time-categorization task (L = laboratory, S = stationary, D = driving).

As can be seen in Fig. 6.4a, this effect was primarily attributable to the changes in attentional and visuomotor demands between the stationary car and the driving condition. There was also a significant main effect of Time Intervals $F(4,108) =$

7.54, $p < 0.0001$). Of the five time intervals, the shortest (750 ms) produced the slowest mean RTs (651 ms), probably because of the combination of a short preparatory interval (expectancy factors; see Poulton, 1973) and the low probability of the yellow light stimulus (which conditionally increased with elapsed time within a trial). The fastest mean RTs were found in the 1750- and 2250-ms intervals (both 594 ms), which may be explained by the rather easy decision compared with the 2750-ms duration interval. There was no significant interaction between Groups and Task Conditions, or between Groups and Time Intervals, which means that for all groups RTs equally increased from the laboratory to the field (see Fig. 6.4a).

As can be seen in Fig. 6.4b, error rates were different among groups, $\chi^2(2) = 16$, $p < 0.0005$. Separate analyses indicated that the older subjects did not make significantly more errors than did the controls. Task conditions produced a main effect that was associated with all changes in task demands from the laboratory to the driving condition, $\chi^2(2) = 60$, $p < 0.0001$. The contribution of an order effect cannot be ruled out. However, the long rest period, the limited number of trials of this experiment, and the fact that for all groups the data of Experiment 1 appeared to be stable over the consecutive blocks make it unlikely that the effect of Conditions is confounded by an order effect. There was also a strong main effect of Time Intervals, $\chi^2(9) = 470$, $p < 0.0001$.

Error percentages varied substantially from the 750-ms (4%) and 5250-ms (2%) intervals to the difficult 2750-ms (37%) and 3250-ms (30%) intervals. Especially for the patients, error rates substantially increased from the laboratory to the field conditions. This was signified by an interaction between groups and Task Conditions, $\chi^2(4) = 13$, $p < 0.05$. Separate analyses indicated that the increase in errors by the older subjects in the field conditions was not significantly different from the controls' error rates. A subsidiary analysis of the error rates over only the brief (< 3000 ms) intervals showed the same main and interaction effects. An interaction between Groups and Time Intervals indicated that the patients made most incorrect responses in the brief intervals, whereas for both other groups error rates were more equally distributed around the 3000-ms decision margin, $\chi^2(18) = 57$, $p < 0.0001$.

6.3.3 Conclusions

In general, patients and, to a lesser degree, the older subjects had prolonged RTs in all task conditions. In contrast to the older subjects, patients made more errors than did controls. With increasing degrees of similarity to actual driving, patients' error rates disproportionately increased, though their brake RTs did not increase more rapidly than did control subjects'. This kind of trade-off strategy may have

detrimental consequences for driving safety in real traffic. With respect to the older subjects, these findings are compatible with the notion that older people generally tend to take more time in task performance while their accuracy remains unaffected (Welford, 1977a, 1981). Increasing RTs were determined only by changes in visuomotor and attentional task demands between the stationary and driving conditions, whereas accuracy effects were determined by all changes in task demands from the laboratory to actual driving. The RT differences between the controls and the experimental groups did not change from the laboratory to the field, but differences in accuracy increased. In contrast to the older subjects and controls, the patients made more incorrect time estimations, especially in the intervals shorter than 3000 ms. This finding suggests that brain damage causes a tendency to overestimate the length of short time intervals.

6.4 Experiment 3: Platoon car following

Decreased speed of information processing may have detrimental consequences for those parts of the driving task in which perception-response speed is critical. Platoon car driving (when two or more vehicles closely follow one another) may be considered one of those critical situations. During platoon car driving, perception-response speed may be too low to allow the driver to adapt to the speed changes of the traffic stream ahead. This effect may be increased by increasing task complexity or task demand (e.g., Cerella, Poon, and Williams, 1980)—for example, when frequent steering actions and speed changes are required. Therefore, in the third experiment brake RT was investigated in a platoon-car-following task in high and low task-demand conditions. It was expected that brake RTs of the brain-damaged and older subjects would increase disproportionately relative to the control subjects as a consequence of increasing task demand. Also, in the second part of this experiment three variables were measured that were supposed to reflect one's ability to quickly and/or accurately adapt to speed changes of leading traffic.

6.4.1 Method

Subjects were the same as in the former experiments. The general instruction in both parts of Experiment 3 was to follow a lead car at a constant distance of about 15 m. This lead car was equipped with a speed sensor, an encoder, and a transmitter. The subjects' car contained a receiver, a decoder, and a PDP 11-03 computer. In the first part of this experiment (brake RT) the driver of the lead car gave brake signals by pressing the brake pedal lightly for about half a second.

Eighty brake signals were given at irregular intervals over a 10-km closed road without other traffic. Subjects were instructed to respond as quickly as possible by pressing the brake pedal. The intervals between the brake signal and subjects' pedal responses constituted the brake RTs, which were recorded by a computer. Brake RTs longer than 2 s and missed trials were recorded as errors. Task load was varied by dividing the path into a straight section (5 km) with constant speed (40 km/h) and a winding section (5 km) in which driving speed of the lead car varied between 20 and 55 km/h. These conditions were counterbalanced for order effects. In both conditions 20 practice trials were given.

In the second part of this experiment (speed reproduction) subjects had to reproduce the speed pattern of the lead car (which was 15 m ahead) as quickly and accurately as possible. Speed of both cars was recorded over a 3-km path. In advance, the task was practiced for 3 min on a 2-km stretch of straight road. In the second part of this experiment speed of the lead car was varied between 20 and 55 km/h. In both parts the standard deviation of successive driving speeds was about 10 km/h.

6.4.2 Results

For the second part of the experiment the speeds of the cars over time were correlated to derive three measures:

1 The unshifted correlation (r) between the speeds of the two cars over time. This correlation can be considered the best representation of total task performance.
2 The delay time to obtain maximum correlation. The two cars produced two similar time-shifted speed signals. The correlation between these signals, therefore, will vary when the following car's signal is shifted in time relative to the lead car's signal. The time shift to obtain maximum correlation is the delay time, which can be considered a measure for the global delay or RT in following the changes in speed of the lead car.
3 The maximum time-shifted correlation as a measure of the accuracy by which the subject reproduces the speed of the lead car.

For this speed reproduction part of the experiment the road was divided over five equal stretches that served as replications for data analyses. ANOVAs on brake RTs, delay times, unshifted correlations and maximum correlations indicated that each of the correlation measures of both the patients and the older subjects was lower than that of the control group, $F(2,27) = 7$, $p < 0.01$, and $F(2,27) = 5.5$, $p < 0.01$, respectively. Separate analyses indicated that brake RT and delay time were significantly prolonged only for the patients, $F(1,18) = 11.0$, $p < 0.005$, and $F(1,18) = 6.7$, $p < 0.05$, respectively. For both brake RT and delay time the patients were almost 40% slower than the controls (see Table 6.1). The brake RT

data showed a significant effect of task demand: subjects responded slower when driving speed of the lead car was varied and the road was winding, $F(1,27) = 21.1$, $p < 0.0005$. RTs of the patients tended to increase more than those of the controls and older. The interaction between groups and task demand, however, was not significant.

Table 6.1   Mean values of Brake RTs, Delay Times, Maximum Correlations, and Unshifted Correlations of Control Group, Patients and Older Subjects.

	Brake RT (ms) Task Load		Delay Times (ms)	Maximum Correlation	Unshifted Correlation
	Minor	Heavy			
Controls	592	649	980	0.98	0.92
Patients	784	906	1370	0.97	0.84
Older	655	764	1110	0.97	0.88

Error rates of the older subjects in the minor task load condition (2%) were between those of the patients (3%) and the controls (1%). For the experimental groups error rates doubled with increasing task load. Because of these low error frequencies, neither of these effects was significant.

6.4.3 Conclusions

That patients were slower and less accurate than control subjects is indicated by their slower brake RTs, higher delay times and less accurate speed reproduction. Older drivers' performance was poor only on speed reproduction accuracy. This result runs counter to experimental documentation (Craik, 1969; Welford, 1977a, 1981; van Wolffelaar et al., in press) that older people generally tend to be slower but show equal or higher accuracy scores than do younger people. This, however, can be true only when accuracy can be increased by taking more time. In the present task—and in many other practical situations—accuracy could not be increased by using extra time. On the contrary, longer delay times would increase the difficulty of accurate speed reproduction because the distance between the cars, which was the primary stimulus in the present task, would become more variable. Compared with the control group, brake RTs of both experimental groups did not disproportionately increase with increasing task load. This finding suggests that in driving tasks, RT measures are not as sensitive for increasing task

demand or task complexity as they are in most laboratory tasks (e.g., Cerella et al., 1980; Miller, 1970; van Zomeren and Deelman, 1976).

6.5 Correlations

The participation of the same subjects in three experiments enabled the comparison of intraindividual performance on different tasks. For every group, four laboratory predictors (RT and error rates in the laboratory condition of the time-categorization task and on the discrete-choice task) were correlated with four criterion measures (brake RT, delay time, maximum correlation and unshifted correlation on platoon car following).

Table 6.2 Correlation coefficients among the Four Laboratory Measures and the Four Driving Measures.

Driving Measures (Experiment 3)	Laboratory Measures			
	Time Categorization (Experiment 2)		Discrete Choice (Experiment 1)	
	RT	*Error %*	*RT*	*Error %*
Patients				
Brake RT	0.94***	0.65*	0.47	-0.36
Delay Time	0.65*	0.52	0.08	-0.04
Maximum Correlation	-0.36	-0.55*	-0.34	0.06
Unshifted Correlation	-0.72**	-0.81***	-0.06	0.06
Older Subjects				
Brake RT	-0.06	-0.24	0.35	0.25
Delay Time	-0.13	0.13	0.38	-0.03
Maximum Correlation	-0.31	0.18	-0.36	-0.42
Unshifted Correlation	0.17	0.20	-0.34	-0.03
Controls				
Brake RT	0.47	0.08	0.20	-0.07
Delay Time	0.15	-0.46	-0.33	0.49
Maximum Correlation	0.00	-0.33	0.50	-0.78***
Unshifted Correlation	-0.33	0.25	0.27	-0.61*

* = $p < 0.05$; ** = $p < 0.01$; *** = $p < 0.005$.

As can be seen in Table 6.2, significant product-moment correlations between laboratory and driving task measures were almost completely limited to the patient group. For the older subjects and the controls more correlations might

have become significant had more subjects been used. However, these probably would not become very impressive, considering that most of the present correlations were low and sometimes even in the unexpected direction. With respect to the patients, the predictive value of both RT and error rate in the time-categorization task was substantially higher than that of RT and error rate on the discrete-choice task. The latter finding suggests that RT tests based on time estimation may be more suitable for predicting speed-related driving abilities than are the more usual RT tests based on discrete stimuli.

6.6 Discussion

6.6.1 General findings

Experiment 1 showed that perception-response speed of the older and, to a minor degree, the patients decreased disproportionally with increasing difference in subsequent compound stimuli. Short response-stimulus intervals did not have such an effect, which implies that only partial confirmation was found for the hypothesis that brain damage or aging causes persistent neural noise.

This finding may have two practical implications. First, test sensitivity to brain damage and especially aging may be increased by merely taking into account the RTs on alternating stimulus sequences. Second, RTs of these subjects may increase more than RTs of others in situations in which paced responses have to be made to many different stimuli—for example, driving downtown during rush hour.

In Experiment 2, RT effects were associated with the information-processing and visuomotor demands specific to car driving as a complex dual-task, whereas accuracy effects were associated with all differences between the laboratory task and the actual driving situation. In this experiment both the patients and, to a lesser degree, the older subjects were slower than the controls. These between-groups differences did not change significantly by increasing task similarity to actual car driving. This means that for both older subjects and brain-damaged subjects, effects of behavioral slowing as measured in laboratory tasks will not substantially increase during actual driving.

The Brake RT data from Experiment 3 lead to a similar conclusion: i.e., that the RT increase of the experimental groups with increasing demands of the primary driving task was not greater than that of the controls. This relative insensitivity of speed-related performance measures was also demonstrated by a decreased accuracy of both experimental groups in the speed reproduction part

of the car-following task, whereas delay times were prolonged only for the patients.

6.6.2 Older subjects

Older subjects were particularly slow (slower than the brain-damaged subjects) in the choice RT task consisting of compound stimuli. This result may imply that older subjects have difficulties with handling *separate* stimuli that *in combination* specify the correct response. This corroborates results of an experiment conducted by Allen and reported by Welford (1958, pp. 193-198) showing that older subjects were unable to combine individual verbal propositions into an overall conclusion, whereas most young subjects had little difficulty in performing the task correctly.

Given that the criterion scores of Experiment 3 were expected to be dependent on perception-response speed, the poor correlations between the laboratory RT tasks and driving performance for both the older subjects and the controls may be considered rather surprising. However, with reference to the young subjects, this finding reflects the low RT variability among normal young subjects (Nettelbeck, 1980), indicating that interindividual differences in RT performance are not a function of significant or stable differences in sensorimotor capacities.

Apart from the low correlations among laboratory and driving RT tasks, speed-related differences between the older subjects and the controls were not significant in the platoon-car-following tasks (brake RT, delay time), even when task load was increased. This result corroborates data of Olson and Sivak (1986), who found about the same brake RT distributions in conditions of unexpected roadway hazards for young and older drivers. These data, and the absence of significant correlations between tasks, seem to conflict with the extensive documentation of a general slowing in information-processing speed with age, which is considered mostly a rather basic phenomenon (e.g., Birren et al., 1980; Salthouse, 1985; Welford, 1965). However, the absence of both of correlations and of a significant age-related slowing of brake responses is compatible with previous experiments documenting reduced RT differences, or even equal RTs, among different age groups as a consequence of extended or longitudinal practice (e.g., Murrell, 1970; Smith and Greene, 1962). Such practice may counteract the trend toward slower performance with increasing age. In addition, the present data are in support of the suggestion, made by Fisk, McGee, and Giambra (1988), that previously developed well-trained skills may remain effective in old age (see Chapter 9). Because the older subjects were experienced drivers, undoubtedly quick brake reactions on roadway events were frequently required during their individual driving histories.

6.6.3 Patients

The patients were slower than the controls in all task conditions. With increasing visuomotor and attentional similarity to actual driving, the patients' error rate increased more rapidly than did the controls'. Patients' RT increments, on the contrary, kept pace with those of the controls. RT studies show that time taken is a function of task complexity or task demands (e.g., Cerella, 1985; Hale et al., 1987) and that speed and accuracy are commonly compensatory (Pew, 1969). Hence, as task demands increase, more time is required or more errors are made. The present data suggest that slowing of patients on RT tasks mainly emerges as decreased accuracy when the task is more demanding—for instance, when driving is required. This suggestion contradicts conclusions of Stokx and Gaillard (1986), who found equal error rates in laboratory tasks and in elementary driving tasks for the patient and the control group. This finding, however, can be explained by the minor error rates in all tasks used by Stokx and Gaillard, which means that performance variance was almost completely represented by RT scores. The time categorization task required estimation and categorization of time values, which differs from classic choice reaction tasks in which stimuli are usually discrete and unambiguous. Therefore, error rates were high enough for analysis of both error and RT scores.

In contrast to the more usual discrete choice RT task, patients' accuracy and speed on the time categorization task showed substantial correlations with four criterion scores on the platoon-car-following task. This finding may be explained by the inherent resemblance of the time categorization task to information processing during actual driving. In natural settings (e.g., when approaching an intersection), a driver constantly has to make decisions based on time information—for example, judging when to start braking or changing course. Also, considering that the information processing required for discrete-choice RT tasks is externally imposed to a high degree, correlations may be explaind by the absence of this imposed structure in the time categorization task and during driving. Therefore, with reference to brain-damaged patients, it should be emphasized that RTs as well as errors must be considered in a task in which time-estimation responses have to be made.

6.6.4 Conclusions

- Patients were slower in all task conditions (Experiments 1, 2, and 3), whereas the older subjects showed increased RTs only in the choice RT tasks (Experiments 1 and 2). Older subjects were particularly slow (slower than the brain-damaged subjects) in the choice RT task consisting of compound stimuli.

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- Only partial confirmation has been found for the hypothesis that the level of residual neural activity increases as a consequence of brain damage or with increasing age (Experiment 1).

- With increasing degrees of task similarity to actual driving, brain-damaged patients made disproportionately more errors than normal subjects, whereas their RT increments kept pace with those of the controls (Experiment 2).

- Correlations between laboratory RT measures (Experiments 1 and 2) and performance in a driving task in which perception-response speed is critical (Experiment 3) were poor for older and control subjects. Together with the low sensitivity of brake RTs to increasing task demands (Experiment 3), these low correlations weaken the evidence for the idea that high RTs on alternating stimuli might predict problems in busy traffic situations (Experiment 1).

- In contrast to many laboratory RT tasks, in practical situations, speed and accuracy often are positively related. In these situations, accuracy cannot be increased by taking extra time (Experiment 3).

- The absence of age-effects in the speed-related measures in platoon-car-following (Experiment 3) and of significant correlations among these measures and laboratory RT tasks suggest that extended practice before old age may compensate the widely documented trend toward behavioral slowing with increasing age.

- Correlations between laboratory RT measures and temporal measures of driving performance may be substantial for brain-damaged drivers if a predictor is based on speed and accuracy in making time estimations.

Chapter 7

Effects of skill integration and perceptual competition on age-related differences in dual-task performance

7.1 Introduction

A substantial body of experimental documentation shows changes in information-processing abilities with increasing age in adulthood (Birren and Schaie, 1985; Salthouse, 1982, 1985). One change that has been demonstrated in many studies is the performance decrement of older subjects in dual-task situations (e.g., Ponds, Brouwer, and van Wolffelaar, 1988; Talland, 1962; but see Somberg and Salthouse, 1982).

At present, little is known of the causes of impairments of older in multiple-task situations. Welford (1958) argued that older people have difficulty switching among perceptual, memory and response functions. Kinsbourne (1980) suggested that because of cerebral degeneration in old age, the "functional distance" between the active brain loci in dual tasks decreases. This may be manifested by a greater tendency to mutual interference between the necessary mental operations and thus by a deteriorated dual-task performance. A further possibility is that reduced attentional resources in older people may lead to shallower and less elaborate processing (e.g., Craik, 1977; Craik and Simon, 1980). Craik (1977) therefore suggested that in dual tasks, a relatively large proportion of older people's processing capacity is taken up in "programming" the division of attention, leaving fewer resources to carry out the subtasks themselves. Probably the best-known hypothesis comes from Salthouse (1982), who argues that there may not be specific aging-related problems in dual tasks but that dual tasks may represent just one of several ways to increase *task complexity*. In two experiments (Salthouse, Rogan, and Prill, 1984; Somberg and Salthouse, 1982) this suggestion seemed to be verified. Two recent experiments reported by McDowd and Craik (1988) suggested that older people are penalized on dual tasks because such tasks represent only one form of task complexity. The general idea behind this *complexity hypothesis* is that as a consequence of decreasing speed of information-processing operations (general slowing) with increasing age (e.g., Salthouse, 1982, 1985), the magnitude of age-related differences in task performance is proportional to the difficulty or complexity of the task.

The present experiment was undertaken to generate more data concerning conditions that may affect age-related differences in dual-task performance. These data may give more insight into possible underlying processes affecting task performance with increasing age. The critical task variables in this experiment were adopted from current notions in the area of human performance theory. In a recent paper Neumann (1987) suggested that skills necessary for task performance are hierarchically organized in the human nervous system. According to Neumann these skills can be integrated into a common, higher-order skill. This means that time-sharing tasks cease to be experienced as dual. For example, skilled oral reading is a continuous task requiring an eye-voice span of several words; hence formally spoken oral reading is a dual task, yet it is not usually considered as such. One may presume that invariant relations among subtasks may facilitate the integration of separate skills into higher-order skills. For example, in dual-tracking tasks identical movements of two separate pointers will increase the coherence (the number of invariant relations among the subtasks) of the dual task as a whole. In practical situations such as car driving or flying an aircraft, many aspects of the task are related or dependent. This task coherence, which is a property of the dual task which emerges from the relation between the subtasks, may facilitate the integrated uptake of multiple sources of information, thereby reducing attentional demands and improving task performance. It is well known that with increasing age the neural organization in the brain degrades—that is, the number of synaptic connections between axons and dendrites decreases (e.g., Scheibel, Lindsay, Tomiyasu, and Scheibel, 1975). Hence, one may expect older subjects to be less able to combine related actions or to incorporate invariant information from different sources. Thus, based on the notion of skill integration, age-related differences in dual-task performance were expected to increase as integration of skills for dual-task performance was facilitated.

Another factor that may affect age-related differences in dual-task performance is the perceptual, cognitive or motor faculties for which tasks compete. When two tasks compete for identical faculties, one may expect dual-task performance to be severely limited by the constraints of these faculties. People may then have to perform the two activities in a serial mode, addressing one task at a time while neglecting any others (Wickens, 1989). However, when subjects are able to integrate their skills for dual-task performance, they may be able to partly overcome these limitations. Therefore it was expected that the effects of competition among subtasks would be reduced when subtasks became more coherent, thereby allowing skills to be integrated. Because age-related differences were expected to be affected by skill integration, it was predicted that the degree to which integration limits the effects of competition also would be affected by age. For the present study the effect of competition was important only insofar as it influenced the effects of integration. Thus the degree to which competition effects are affected by age was of secondary importance.

In the present study the predictions were tested with two simple tracking tasks, which were calibrated for individual ability levels. By this method I was able to control for age-related differences already present in single-task performance (Somberg and Salthouse, 1982).

7.2 Method

7.2.1 Subjects

Twelve right-handed older men (mean age 70.8 years, *SD* 3.9) and twelve right-handed young men (mean age 24.5 years, *SD* 2.2) participated in this experiment. The subjects were matched on educational and professional level by the method in Luteyn (1976). They volunteered in response to a local advertisement inviting healthy old or young adults to participate in a study involving a motor-dexterity task. None of the subjects had a history of neurological or cardiovascular disease, and all were healthy and had normal or corrected-to-normal visual acuity (Landolt C test). Age-corrected group scores on the Digit Symbol Substitution subtest of the Wechsler Adult Intelligence Scale were not significantly different ($p > 0.05$).

7.2.2 Experimental tasks and apparatus

Two single-axis compensatory tracking tasks were used, one in the horizontal and one in the vertical dimension.

Compensatory tracking

Two analog one-dimensional joysticks were positioned in front of the subject, one for the left hand and one for the right hand. A single-axis compensatory tracking task had to be carried out with each joystick. With the left-hand joystick, horizontal pointer movements had to be nulled, and with the right-hand joystick, the same task was to be done for a vertically moving pointer. Right and left deflections of the left joystick produced pointer movements in the horizontal axis, whereas fore and aft deflections of the right joystick were translated as up and down movements, respectively, on the screen. Fig. 7.1 shows the configuration of the stimulus display with moving pointers, the stationary targets and the joystick panel.
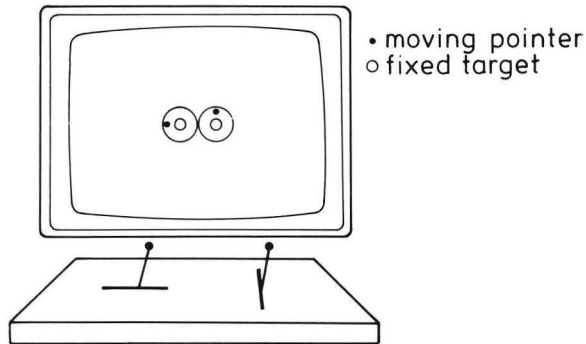
Fig. 7.1 Schematic representation of the stimulus display.

Apparatus and disturbance inputs

The pointers on the monitor screen were dots 0.07° diagonally. A 1° rotation of the joystick resulted in a 0.24° translation of the pointer on the screen (position control). The inside diameter of the target circle was 0.6°. The pointers on the screen were continuously disrupted by a band-limited (frequency <1 Hz), random forcing function (the track). The standard deviation of the track was individually adjusted (see procedure). In each condition the same tracker was used, which consisted of 60,000 points that were computed before the experiment. To allow continuous transgression when the end was reached, the beginning and end of the track were adjusted. For each experimental trial the starting points within the track were chosen randomly. Experimental control and data acquisition were governed by an IBM AT3 personal computer.

Experimental conditions

Nested under age, a within-subjects design was used which consisted of four conditions created by crossing two levels of skill integration and two levels of visual competition. The two conditions of integration were created by using identical versus different points within the track as starting points for vertical and horizontal tracking. The consequence of an identical starting point is a covariation of both pointer movements (a synchronization of right with upward movements and of left with downward movements—task synchronization), which increases the degree of dual-task coherence. In the other condition of skill integration different starting points within the track were used, and thus the pointers for both axes were independently disturbed.

It was hypothesized that the degree to which tasks compete for peripheral visual resources is proportional to the visual distance between the pointers. Competition was therefore manipulated by varying the distance on the screen between the targets of the horizontally and vertically moving pointers. In the condition of minor visual competition, the distance between the left and right targets should be small enough that stimuli could be perceived simultaneously and may be processed in parallel. In the condition of major competition, however, the distance should be great enough to prevent subjects from performing the tasks while looking between the targets. The subjects should have to successively fixate the stimuli and process the information in a serial mode. Visual angles between targets of 3° and 18° were chosen as small and large target distance conditions, respectively. In the 3° conditions—as opposed to the 18° conditions—structural visual interference effects were assumed to be minimal, because this angle would keep the pointers within the "stationary field" of the eyes, where stimuli can be processed in parallel without eye movements (Sanders, 1963; Sanders and Houtmans, 1984). In pilot studies it appeared that, irrespective of age, it was impossible for subjects to perform the 18° tasks well without shifting their eyes between the subtask stimuli. In contrast, in the 3° conditions looking between the targets appeared to be the optimal strategy and was adopted spontaneously by most subjects.

For the single-axis tasks there was only one pointer, which moved in one dimension.

Data collection

Error was sampled 50 times per second. Performance on each tracking axis was measured by computing the root mean square (RMS) tracking error. In the experimental conditions, RMS tracking errors on each axis were integrated over 60-s intervals.

7.2.3 Procedure

Subjects were seated approximately 90 cm from a phosphoric monitor in a dimly illuminated, sound-attenuated room. They were continuously monitored via a camera. The experimenter was situated in an adjacent room from where he could communicate with the subjects via an intercom.

The experiment consisted of two stages: a practice stage and an experimental stage. The practice stage began with a short briefing about the general nature of the experiment. Subjects were instructed to direct equal amounts of attention to both tracking tasks. In order to minimize strategic differences in the 3° condition, subjects were instructed to look between the targets. They were also informed about the presence or absence of synchronized pointer movements and the possible benefits of the former.

After receiving general instructions, subjects practiced single-axis and dual-axis tracking in three repeated sessions. Each practice session comprised one 5-min trial for

each single-axis condition (right/vertical and left/horizontal) and one 5-min trial for each dual-axis condition, created by two levels of task synchronization and two levels of target distance. A control study showed that after two of these sessions both age groups attained a single- and dual-task performance (Korteling and Burry, 1989). Within a practice session the single-task conditions always preceded the dual-task conditions. The order of single-task conditions and the order of dual-task conditions were counterbalanced.

In order to equate task performance for all subjects for each single task during single-task practice, the standard deviation of the track was adjusted for each subject for each subtask. The criterion for this calibration procedure was an RMS error of 13 arcmin on the screen. The standard deviation of the track during the third single-task session was the track standard deviation for the dual-task sessions. This individual calibration procedure prevented problems with the interpretation of age-related dual-task performance differences given initial age-related or subtask-related discrepancies.

After practice, dual-task performance was tested under the four described conditions in which the horizontal and vertical tracking tasks were carried out simultaneously. Each condition was carried out in one trial, which consisted of two intervals of 5 min interrupted by a 1-min break. The order of dual-task conditions was counterbalanced between groups.

On a single day two subjects were tested. They alternated such that one subject relaxed while the other performed one dual-task or single-task trial.

7.3 Results

7.3.1 Single tasks

Although single-task difficulties were individually adjusted, it was possible to measure single-task performance using the track standard deviations that were attained by the subjects in the calibration session. These deviations may be interpreted as indicators of horizontal tracking ability with the left hand and vertical tracking ability with the right hand. On these standard deviations a 2 (Age) $\times$ 2 (Hand/Axis) analysis of variance (ANOVA), with age as a between-groups variable, was carried out. This demonstrated a main effect of age, $F(1,22) = 23.3$, $p < 0.001$.

A mean calibrated track standard deviation of 47 arcmin for the young subjects and 36 arcmin for the older subjects shows that the young subjects' tracking ability was superior to the older subjects'. For both the older and young subjects, task difficulty appeared to be the same for the left- and right-hand subtask.

7.3.2 Dual tasks

In order to identify the task conditions that produced an age-related difference in time-sharing performance, a 2 (Age) × 2 (Task Synchronization) × 2 (Target Distance) × 2 (Hand/Axis) ANOVA was carried out on the experimental RMS tracking errors. Mean tracking errors for all experimental conditions are shown in Table 7.1.

Table 7.1 Mean tracking errors (arcmin) in the experimental conditions for both age groups collapsed over hand/axis.

	Target Distance 3°		Target Distance 18°	
	Task Synchronization		Task Synchronization	
	Present	Absent	Present	Absent
Young Subjects	16.5	17.6	22.1	24.2
Older Subjects	17.5	18.0	23.0	23.2

The main effects of synchronization, $F(1,22) = 28.4$, $p < 0.0001$, and target distance, $F(1,22) = 302$, $p < 0.00001$, were significant. Dual-task performance became more efficient as skills could be integrated and/or as visual competition decreased. The difference in performance between the two tasks (horizontal/left and vertical/right) was not significant, which demonstrates that as a group subjects directed equal amounts of attention to each tracking task. The main effect of age also was not significant. This, however, can be explained by the selective effect of synchronization on age groups. Fig. 7.2 illustrates the significant interaction between age groups and task synchronization, $F(1,22) = 8.6$, $p < 0.01$.
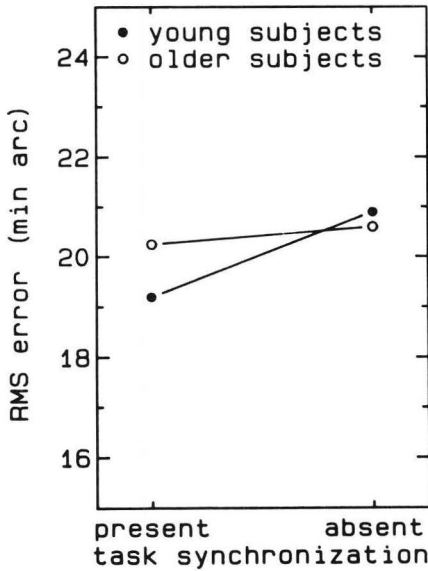
Fig. 7.2 Tracking errors for young and older subjects, as affected by two levels of task synchronization.
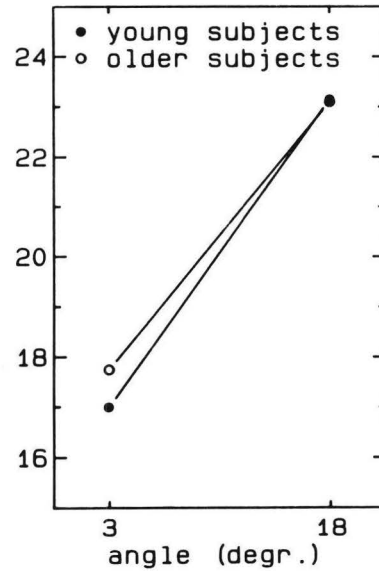
Fig. 7.3 Tracking errors for young and older subjects, as affected by two levels of target distance.

The younger subjects were more capable than the older subjects in integrating tracking skills. This yielded a substantial reduction in tracking error for the young subjects. When task synchronization was absent, the difference between groups was not significant. Fig. 7.3 shows that the main effect of target distance was not significantly different between age groups ($p = 0.17$).

Finally, an interaction among groups, task synchronization and competition was found, $F(1,22) = 6.11$, $p < 0.05$. Fig. 7.4 shows the difference in task performance between the two conditions of target distance as a function of task synchronization. The interaction indicates that for young subjects, the effect of competition decreased by synchronization, whereas for older subjects, this was not the case. In other words, only the young subjects benefitted from skill integration in order to overcome the effects of visual competition. Apparently the effect of synchronization for the young subjects is not great when the tasks can be performed simultaneously, but when tasks compete for the same resources, task synchronization makes a great difference. For the older subjects the latter seems not to be the case. Another, more general, conclusion is that these data show that age-related differences in dual-task performance depend on task variables. Although the

complexity hypothesis is compatible with this conclusion, this is not to say that the present data completely support it. This topic will be addressed in the discussion section.
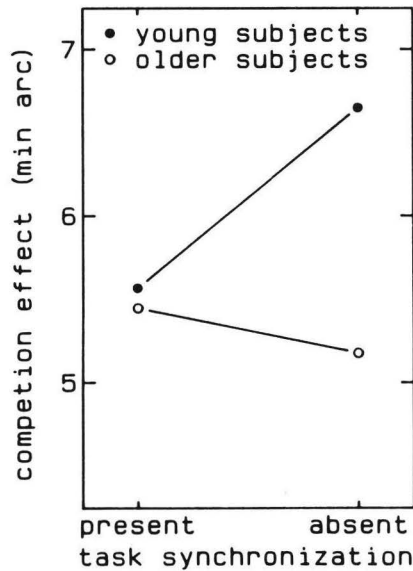

Fig. 7.4 The effect of visual distance (RMS difference between the two conditions of visual distance) for young and older subjects, as affected by two levels of task synchronization.

There was no interaction between groups and subtasks, which indicated that both groups distributed equal amounts of attention to the tracking tasks. There was also no interaction between task synchronization and visual competition.

7.4 Discussion

The present study was aimed at the effect of skill integration on age-related differences in dual-task performance under two conditions of visual competition. A substantial age-related difference was found when pointer movements in both tracking tasks were synchronized; only for the young subjects did this facilitate integration of tracking skills. The data also showed that skill integration could be used to decrease the negative effect of visual competition. This, however, was accomplished only by the young subjects. The effect of visual competition was not significantly different between age groups.

The complexity hypothesis states that the magnitude of age effects should increase with task complexity or the requested number of mental operations (e.g., Cerella et al., 1980; Salthouse, 1982). According to the rationale presented in the introduction, task synchronization allows the combination of skills; this reduces the number of task components, which makes the task easier —that is, it makes the task more like a single task. Because the older subjects were unable to integrate the subtasks, for them the condition with synchronized subtasks was not easier than the condition with independent subtasks. This caused age-related differences to increase with decreasing task complexity—that is, when pointer movements were synchronized. Consequently the main finding of the present experiment is not in accordance with the complexity hypothesis. This, however, may be explained by the notion that speed or capacity limitations determine dual-task performance only when subjects have to deal with independent stimuli at the same time. In general, when elements of subtasks are not coherent, dependent, or invarient, or do not correspond, a dual task does not afford the possibility to combine subtasks. In that case, subtasks have to be kept separate such that task performance may depend only on the number of mental operations a subject can perform per unit of time. The magnitude of age-related performance differences will then be proportional to the complexity of the task or the required number of mental operations. However, when different stimuli, required processing operations, and/or responses in a dual task are dependent or coherent, subjects may integrate them in order to overcome capacity limitations. The complexity hypothesis does not account for such processes, caused by emergent characteristics of dual tasks.

Modern research has confirmed this notion of *perceptual integration* in dual tasks. An example of this is the *word superiority effect* (Massaro, Taylor, Venezky, Jastrembski, and Lucas, 1980; Paap, Newsome, McDonald, and Schvaneveldt, 1982; Reicher, 1969; Werner, 1990) and by the *object superiority effect* (e.g., McClelland, 1978; Wandmacher, 1981): under certain conditions the perception of wholes (words or object drawings) may be better than that of parts (letters or lines embedded in object drawings). Very closely matching the present data are the results of Massaro (1985), which indicate an integrated uptake of multiple sources of information only when that information specifies the same event. In conclusion, the complexity hypothesis may be an adequate explanation for dual-task situations with independent subtasks. However, when it is possible to combine subtasks, skill integration may also become a significant determinant of task performance, undermining the generality of the complexity explanation.

The finding of equal effects of increasing competition in both age groups is also not compatible with the complexity hypothesis. This, however, may be explained by young subjects' superiority in registering and processing perceptual information *in parallel*. Although it is not well established how much of this effect may be explained by peripheral extrafoveal decline (e.g., Cerella, 1985) or by attentional decline (e.g., Hoyer and Plude, 1980), parallel information processing was much more important in the

conditions with a 3° distance between targets than in those with an 18° distance. In the 18° conditions the subtasks could be performed only serially ('time swapping'; Wickens, 1989), like two single tasks. This, of course, is more comparable to the mode of task performance in the single-task (calibration) conditions than to the mode of task performance in the 3° conditions. Therefore the calibration procedure, controlling for initial performance differences on a single-task level, could successfully eliminate age-related performance differences in the more difficult 18° conditions. However, that the calibration procedure could not account for performance differences in the 3° conditions may have been partly the result of superiority of the young subjects in parallel information processing. Such superiority may have favored the young subjects' performance only in the 3° conditions, which in turn, together with the calibration procedure, may have nulled the supposed Age × Complexity effect (Fig. 7.3).

The question may be raised as to whether more extensive practice might have eliminated the present effects; this seems rather implausible. First, after the subjects practiced, single-task difficulties were individually adjusted so that a possible effect of age on speed of mastering a new task was excluded. Second, McDowd (1986) showed that age effects in simultaneously performing a pursuit tracking task and an auditory choice reaction task do not seem to be caused by a transient age-related difficulty with these tasks.

Factors other than practice may determine why older subjects seem to integrate their skills so ineffectively. For instance, they experience difficulties with the bimanual coordination of the movements of their hands; Stelmach, Amrhein, and Goggin (1988) recently presented evidence for this suggestion. Alternatively, it may be presumed that older persons are less capable of behavior control—that is, programming, controlling and monitoring behavior by modifying actions with respect to task conditions. Both movement coordination and behavior control are functions associated with the prefrontal parts of the frontal lobes (e.g., Luria, 1973), which means that the present findings are compatible with existing neuropsychological (Albert and Kaplan, 1980), electrophysiological (Woodruff, 1982), and neuropathological (e.g., Brody and Vijayashankar, 1977; Scheibel and Scheibel, 1975) evidence for a disproportional decline of frontal lobe functioning with increasing age. It may thus be supposed that the degradation of neural connections, especially in the frontal areas, make older subjects less able to perform coherent dual tasks, such as car driving, efficiently. This may be caused by limitations in the integrated uptake and processing of information from multiple sources and/or limitations in the combination of related actions. Which explanation is the most appropriate can be decided only on the basis of further investigation.

Effects of age and task similarity on dual-task performance

8.1 Introduction

Difficulties in performing two or more simultaneous activities have been postulated to be responsible for many deficiencies in psychomotor and cognitive functioning with increasing age in adulthood (Broadbent and Gregory, 1965; Caird, 1966; Clark and Knowles, 1973; Craik, 1965; Inglis and Ankus, 1965; Inglis and Caird, 1963; Korteling, 1991; Ponds, Brouwer, and van Wolffelaar, 1988; Salthouse, Rogan, and Prill, 1984; Talland, 1962; Wright, 1981). The task variables that may determine the magnitude of this age effect in dual tasks, have not been extensively investigated. Knowledge concerning these variables may provide more insight into possible underlying mechanisms determining aging-related performance deteriorations.

In skilled tasks that permit automatic processing (e.g., Posner and Snyder, 1975; Schneider and Shiffrin, 1977; Shiffrin and Schneider, 1977), differences between young and older subjects tend to disappear (Hasher and Zacks, 1979). However, this may only be true when automatic processes are developed *before* old age. Fisk, McGee, and Giambra (1988) demonstrated that *after* old age, the degree with which older subjects can acquire new automatic processes declines.

Aging is also accompanied by slowing in information processing (e.g., Birren, Woods, and Williams, 1980; Salthouse, 1982, 1985), or, more explicitly, by neuronal noise (Crossman and Szafran, 1956; Layton, 1975; Welford, 1958, 1965, 1981). According to Myerson, Hale, Wagstaff, Poon, and Smith (1990), this noise causes cumulative loss of information in consecutive processing steps, resulting in progressive slowing of successive processing steps. This is the basis of the *slowing-complexity hypothesis*, which states that progressive slowing in succeeding processing steps causes performance differences between age groups to increase disproportionally with task complexity (see also: Cerella, Poon, and Williams, 1980; Salthouse, 1982). The substantial age-related performance differences in dual tasks may therefore be caused by the mere complexity of these tasks, and nothing else (e.g., McDowd and Craik, 1988; Salthouse et al., 1984). In these terms, the absence of an age effect in pure dual-task performance in two experiments reported

by Somberg and Salthouse (1982), may well be explained by the very simple nature of the tasks used.

Recently, it has been assumed that *similarity* between subtasks may be an important determinant of dual-task performance (e.g., Wickens, 1989). Similarity involves concrete task characteristics which emerge from the *combination* of subtasks, such as spatial or temporal similarities or similarity of color or form, or similarities in the semantic domain. Hence this concept is based on *emergent* characteristics of the dual task in terms of stimulus information, required processing operations, and/or responses. The present experiment addressed possible effects of similarity on the magnitude of age-related differences in dual-task performance.

Increased similarity may affect dual-task performance positively and negatively. When similarity refers to corresponding, related, or coherent inputs, processing operations or actions or to common stimulus-response mappings, timing mechanisms, or goals, task performance may improve because the coordination or integration of subtasks is facilitated (e.g., Duncan, 1979; Peters, 1977). This can be termed *coherent similarity*. With reference to age-related differences in this respect, Korteling (1991) found that in a simple dual compensatory tracking task, young subjects did not outperform the older subjects except when the pointers of two tracking tasks made synchronous movements. Apparently synchronization of constituent tasks enabled only the young to integrate or combine these separated activities. This can be termed *skill integration* or *performance integration*. It was concluded that the older may be less able to perform coherent dual tasks efficiently, possibly because of limitations in the integrated uptake and processing of information from multiple sources, and/or limitations in combining related actions.

Performance integration based on the relationships among subtasks may be conceived as a natural way to overcome interference between activities and to reduce attentional demands. However, if subtasks are completely independent and do not share coherent or common processing routines, it may be impossible to combine actions or, in a broader sense, to integrate skills. In that case performance may only be enhanced by improving basic skills for single-task performance. Hence the degree to which performance in a dual task can be integrated depends on the *a priori* degree of similarity in terms of task-coherence. The more a dual task is designed with coherent subtasks, the more the task may be performed (and experienced) as a single task. For example, piano playing requires simultaneous performance of two tasks with both hands, yet for skilled players these subtasks are related to such a high degree that it is hardly experienced as dual-task performance. The same is true for oral reading (Neumann, 1987). For more about positive effects of task-coherence and integration, see Korteling (1991), Neumann (1987), Paap, Newsome, McDonald, and Schvaneveldt (1982), and Werner (1990).

Similarity may also hamper task performance. This may be the case when tasks are independent and do not employ coherent or common processing routines, but still have

resemblance at a superficial level. This can be termed *incoherent* or *representational* *similarity*. With increasing incoherent similarity, it will be more difficult to keep the tasks separate. Subjects may unintentionally combine the subtasks, such that the constituent tasks may become more susceptible to mutual disruption. Navon and Miller (1987), for example, showed emerging confusions when targets of one task belonged to the same category as nontargets of a concurrent task. Furthermore, it has been shown that the ability to selectively process one of two messages or to shadow two simultaneous messages, is disrupted by increasing semantic similarity between the two (Hirst, 1986; Shaffer, 1975; Treisman, 1964). Task performance may also deteriorate when similarity of subtasks at the stimulus level is different from that at the response level. In that case, the natural relationship between stimulus information and accessory actions may be disturbed. For instance, dual tasks that include a mismatch between levels of integration may produce *incompatibility of integrality* (Fracker and Wickens, 1989). In a dual tracking task, incompatibility of integrality is seen when two one-dimensional pointers (low integrality) have to be controlled with one two-dimensional control stick (high integrality). Because of this partial integration concerning only the response part of a dual task, perceptual and motor actions may easily be confounded.

When integrality of a dual task is made incompatible, or when superficial similarity of unrelated subtasks is increased, subtasks and actions have to become more properly matched. The subject is then required to perform extra, or more precise, mapping operations between stimuli, processing operations, and responses such that the subtasks remain segregated. When people fail to make the proper mapping operations, perceptual or control actions may interfere or be directed to the wrong subtask. In other words, skills activated by performance of one task may easily cause unwanted intrusions into the performance of the concurrent task. This kind of confusion has sometimes been termed *cross talk*. In a dual-axis tracking task characterized by a mismatch between levels of integration and/or by representational similarity between subtasks, performance probably will be hampered by cross talk.

If older people have difficulties in performing extra or more precise mapping operations, increasing similarity among subtasks will be detrimental to their task performance. Evidence for an age-related mapping problem has been found for single tasks. For example, in pursuit rotor tasks, spatial transpositions had a disproportionally adverse effect on older people (Ruch, 1934). The same effect of spatial transpositions has been found for RT tasks (Griew, 1964; see Welford, 1977, for an overview). In dual tasks, mapping problems may be manifested by cross talk and/or eventually a poorer general task performance.

The slowing-complexity hypothesis predicts that age-related differences would increase with the complexity of the general dual-task situation. This means that age-related performance differences would increase with the mapping requirements imposed by the microstructure of the dual task. In order to examine the implications of the universal

slowing-complexity hypotheses and to test the more specific effects of mapping demands on age effects, the present experiment addressed the hypothesis that age effects in task performance will depend on the degree of similarity between independent subtasks.

Subjects performed two simple one-dimensional tracking tasks with perpendicular tracking axes. Display and Control Integrality were independently varied.

Mapping requirements were supposed to increase when tasks were only partially integrated. More complete separation or integration of the subtasks was supposed to increase compatibility of integrality and thus limit mapping requirements. Furthermore, complete integration would make the dual task more like a single task and thus was expected to optimize task performance.

Mapping requirements were also assumed to increase with the degree of axis similarity between subtasks. Therefore, in one condition, separated tracking axes were lined up horizontally (in the same line). This condition could be compared with a condition in which separated tracking axes were perpendicularly orientated.

Performance measures were based on three single-task dependent variables reflecting information processing speed (tracking performance, movement speed, digit-symbol substitution) and two dual-task dependent variables (tracking performance and axis cross talk). Incoherent similarity in dual-task conditions was predicted to produce deteriorated tracking performance, possibly attended by more cross talk.

Because there usually are substantial age differences with single-task conditions, the proper way to evaluate dual-task effects is to express performance deteriorations associated with divided attention as a ratio of single-task performance, or to control beforehand for single-task differences between groups. In the present experiment the latter solution was adopted.

8.2 Method

8.2.1 Subjects

The subjects were 28 adults divided into two age groups, each consisting of ten males and four females. Because of equipment problems, the data of two subjects were incomplete and thus were omitted from consideration. The mean age of the remaining older subjects was 69.7 years (range 64-77, *SD* 4.3); the mean age of their younger counterparts was 25.8 years (range 19-30, *SD* 3.2). By frequency distribution control, the subjects were matched on educational and (ex-) professional level. All subjects were currently healthy and had normal or corrected-to-normal visual acuity. As will appear in the data, age-corrected scores of the subject groups on Digit-Symbol Substitution of the Wechsler Adult Intelligence Scale (WAIS), were not significantly different. Subjects were paid for their participation.

8.2.2 Experimental task and apparatus

The dual-axis compensatory tracking tasks were constructed out of two independent single-axis compensatory tracking tasks.

Control sticks

Two analog control sticks (joysticks) were positioned in front of the subject on a horizontally mounted panel. Subjects had to null vertical and horizontal errors by using either separate controls for each axis or a single integrated control for both. When a control was integrated, it was located near the subject's preferred hand and could be manipulated in two dimensions. Otherwise the control was constrained to move only in one dimension. In the single-task conditions, error had to be controlled in only one axis. Horizontal deflections of the controls always controlled error in the horizontal axis, and forward and backward deflections controlled vertical error (see Fig. 8.1).

Display

Subjects were seated approximately 140 cm from a RGB high resolution monitor (Barco). The pointer on the screen was a dot diagonally 0.07 deg. The inside diameter of the target circle was 0.6 deg. In the single-axis conditions, only one pointer moved in one dimension. In the dual-task conditions, one integrated pointer was disturbed in two dimensions at the same time, or two separated pointers moved in one dimension at the same time. When pointers were separated the visual angle between the two stationary targets (Fig. 8.1) was 2.8 deg. Peripheral visual interference effects were supposed to be minimal, because this angle would keep the pointers within the stationary field of the eyes. Sanders showed that stimuli within the stationary field are simultaneously processed (e.g., Sanders 1963; Sanders and Houtmans, 1984).

System dynamics and disturbance inputs

The analog control sticks were gripped and manipulated by the fingers. The handles extended 10 cm above their pivot and 7 cm above the panel. They moved through an angle of 30 deg with negligible viscosity and inertia. In all experimental conditions, a 1 deg of control movement produced 0.26 deg of pointer movement on the tracking display (position control). Error was created by disrupting pointers by a band-limited (< 1 Hz), pink noise forcing function. In each condition the same track was used, consisting of 18000 points that were computed before the experiment. The beginning and the end of the track were adjusted. For each experimental trial, the starting point within the track was chosen randomly. In the dual-task conditions, the starting points of both subtasks

differed by 9000 points. Error was sampled and stored for analysis with 50 Hz. Experimental control and data acquisition were governed by an IBM AT personal computer.

Experimental variables

For each age group, four dual-task conditions were created by combining two levels of the factor "display integrality", with two levels of the factor "control integrality". Display integrality was varied by using two separate pointers, each moving in one dimension, or integrating them into one pointer moving in two dimensions. Control integrality was varied by using two single-axis controls or integrating them into one dual-axis control. Axis similarity was varied by the creation of a fifth condition which consisted of separated pointers and controls both lined up horizontally (see Fig. 8.1). This condition could be compared with the condition with separate, perpendicularly oriented, controls and pointers.

The single-task design consisted of four conditions formed by the factorial combination of hand (left, right) and tracking axis (horizontal, vertical).
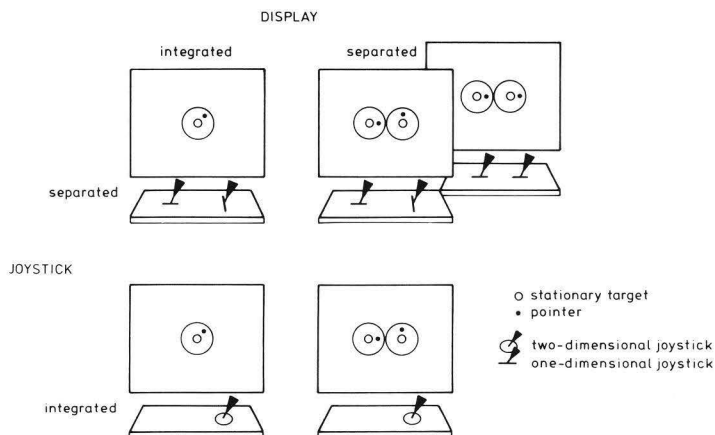

Fig. 8.1 Schematic representation of the stimulus-response configuration in the five experimental conditions.

8.2.3 Procedure

Subjects served for one 1-day session. Each day two subjects were tested such that one subject relaxed while the other performed one block of single- or dual-task trials. They were seated in a dimly illuminated, soundproof room and were continuously monitored

via a camera. The experimenter was situated in an adjacent room from where he could communicate with the subjects via an intercom.

Practice blocks

The practice blocks began with a short introduction about the nature of the experiment. Subjects were instructed always to devote the same amount of total effort to performance regardless of the number of subtasks required. On multiple-task trials, they were instructed to allocate attention equally between the two tracking tasks. In order to minimize strategic differences, subjects were instructed to look between the targets. In previous studies this appeared a superior strategy that was adopted by most subjects spontaneously.

After the general instructions, the subjects practiced in two single-task blocks and two dual-task blocks. The dual-task practice blocks were always preceded by the single-task practice blocks. in order to control for sequencing effects, however, the order of conditions within blocks was counterbalanced between groups. A dual-task practice block was composed of five trials of 100 s; for each dual-axis condition one trial. Trials were interrupted by a 20-s rest period. A single-task practice block was composed of four trials of 180 s each, also with a 20-s break between them. For each single-axis condition one trial was performed.

In order to equate subtask difficulty for all subjects during single-task practice, the degree of pointer movement on the screen had to be adjusted. This was accomplished by calibrating the gain of the forcing function, and thus its standard deviation, for each subject for each subtask. The criterion for the calibration procedure was a root mean square (RMS) error of 0.22 deg on the tracking display. The amplitude gain during each single-axis condition was saved and used to set the deviation of the disturbance signal for the relevant conditions in the next dual-axis block. Of course, in each dual-axis condition, the gains for only the two relevant axis-hand combinations in that condition were used. The main aim of the individual adjustment procedure was to prevent the possibility that age-related differences in dual-task performance would be confounded by initial differences in tracking ability.

Experimental blocks

The experimental blocks consisted of a third single-task block (which was identical to the prior practice/calibration blocks), the paper and pencil test, and five dual-task blocks. The following single-task performance measure were taken:

- Single-task tracking performance was represented by the calibrated standard deviation of the track that was reached by a subject in compensating single-axis pointer movements. The *higher* this

standard deviation, the better a subject nulled pointer movements. This measure was taken over the last 150 s of the error signal for each of the four single-task conditions.

- Single-task compensatory movement speed was calculated from the spectral density function of the error signal. This function represents the division and the weight of the frequencies of pointer movements. Since the disturbance input was low pass filtered at 1 Hz, the proportion of frequencies above 1 Hz in the spectral density function was calculated. For each single-task condition this measure was taken over the last 150 s of the error signal.

- After this third single-task block, the Digit-Symbol Substitution test was administered. This test is recommended as a reliable, age-sensitive, and simple index of an individual's general speed of information processing (e.g., Salthouse, 1985).

Next, the five dual-task blocks were carried out in intragroup-balanced order, each block representing one of the five experimental conditions. A block was comprised of five trials of 100 s, again with a 20-s rest period between them. Based on the error signals over both axes, the two dual-task performance measures were calculated as follows:

- For each condition, RMS tracking error was measured over 20-s intervals for each tracking axis apart. In this manner, 25 error values per axis (5 intervals × 5 trials) yielded the overall tracking performance score for each dual-task condition.

- Axis cross talk refers to the correlations between the error signals of the two tracking axes, and thus reflects the degree to which independently disturbed pointer movements were made dependent by the tracking actions of the subjects. Axis cross talk was measured by calculating over each 100 s interval the correlation (pmc) between the two error signals. When both tracking axes are perpendicular to each other, it may be assumed that correlations, whether positive or negative, are arbitrary. The sign (positive or negative) of eventual correlations may depend on individual idiosyncrasies rather than on meaningful factors. (This idea was substantiated by the finding that the height of the normal correlations varied very unsystematically, even within subjects. Accordingly, most mean values were close to zero and no significant effects were seen.) Therefore, in the four conditions with perpendicular tracking axes, the absolute correlation was calculated. In the condition with tracking axes in line, however, the sign of the correlations between tracking axes was meaningful. When subjects direct control actions for one axis to the wrong axis (or to both axes at the same time), or when they respond less adequately when the pointers are positioned at different sides of the targets, correlations will turn out to be negative. If subjects respond inadequately when the pointers are at the same side of the targets, correlations will be positive. Therefore, in the condition with tracking axes in line, the normal correlation was calculated.

8.3 Results

8.3.1 Single tasks

The data were analyzed with analyses of variance (ANOVA) in which subjects were nested under age groups.

Single-axis tracking

The standard deviations of the track reached during the third single-task (calibration) block may be interpreted as indicators for compensatory tracking ability. The higher the (individually adjusted) track standard deviation, the better a subject was able to control pointer movements to criterion level. These standard deviations were analyzed in a 2 (age) $\times$ 2 (axis) $\times$ 2 (hand) ANOVA.

A mean track standard deviation of 28 arcmin (*SD* 4.4) for the young subjects and 24 arcmin (*SD* 5.6) for their older counterparts was found. This difference between age groups was marginally significant [$F(1,24) = 3.4$, $p=0.075$]. A previous experiment (Korteling, 1991) showed the same effect with a higher degree of significance. This means that the present result can be regarded as cumulative evidence for a small age effect on compensatory tracking performance. There were no main effects of hand or axis. However, there was a significant hand $\times$ axis interaction [$F(1,24) = 14.9$, $p=0.005$]. For the horizontal tracking axis the left hand outperformed the right, whereas for the vertical axis the right hand was superior. This effect was not different for both age groups.

Movement speed

A 2 (age) $\times$ 2 (axis) $\times$ 2 (hand) ANOVA on the proportions of movement frequencies above 1 Hz did not show significant main or interaction effects. There was only a tendency ($p=0.17$) that the young (movement frequencies > 1 Hz: 34%, *SD* 8.5) made quicker movements than the older subjects did (movement frequencies above 1 Hz: 29%, *SD* 9.0). The same tendency with almost identical proportions was found in a previous study (Korteling and Burry, 1989), which may indicate that the spectral density function is a reliable measure. In order to find significant age-related differences on this measure, which was not a major aim of the present study, more subjects will be required.

Digit-Symbol Substitution

Mean raw scores on this WAIS subtest were 63.4 (*SD* 10.2) for the young and 47.1 (*SD* 9.2) for the older subjects. These performance differences were significant [$t(24) = 4.3$, $p<0.005$], indicating that the old subjects had a slower information processing speed than their younger counterparts did. This is in accordance with the fact that scores on Digit-Symbol Substitution decline substantially with age. It was therefore not surprising that the age-corrected, scaled scores of both age groups were not significantly different. This means that the age groups were comparable with respect to this intelligence subtest.

For the old subjects, all these single-task measures were significantly correlated (range: 0.56 - 0.97). For the young subjects, however, only tracking performance was correlated with movement speed (0.88). This is compatible with the idea that, for young and healthy subjects, differences in speed performance are not a clear function of interindividual differences in a specific psychomotor capacity (e.g., Korteling, 1990; Nettelbeck, 1980). On balance, the aggregate single-task measures, which were all supposed to be dependent of information processing speed, indicate that the older subjects were slower than their younger counterparts, and that this slowing may be considered as one single factor in information processing.

8.3.2 Dual tasks

RMS tracking error

Fig. 8.2 shows for both age groups the dual axis errors in each of the five experimental conditions. A 2 (age) × 2 (display integrality) × 2 (control integrality) × 2 (tracking axis) ANOVA with respect to the four compatibility of integrality conditions (perpendicular tracking axes), indicated superior time-sharing capabilities for the young subjects [$F(1,24) = 7.3$, $p < 0.05$]. There were no significant main effects of display or control integrality, or interactions of these factors with age. There were also no significant effects of tracking axes, which means that the calibration procedure for single-task tracking ability had been successful.
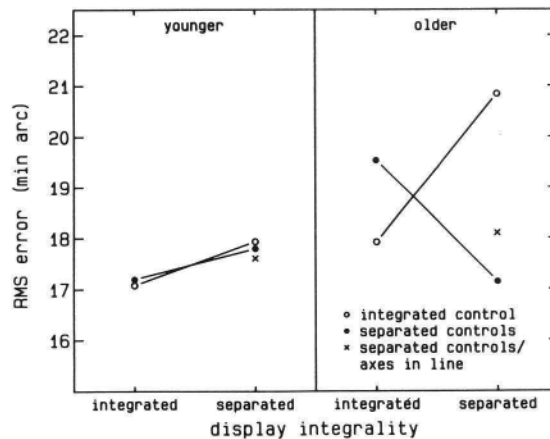

Fig. 8.2 Mean RMS tracking errors for the young and older subjects as affected by display integrality and control integrality. The condition with separated displays and controls is divided into a condition with perpendicular axes and one with axes in line.

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The absence of interactions of the integrality conditions with age, however, is explained by a clear and selective effect of compatibility of integrality. First, there was a significant interaction of display and control integrality [$F(1,24) = 7.9, p < 0.01$]. As can be seen in Fig. 8.2, subjects performed relatively poorly when display and control integrality did not match. Second, this effect was significantly stronger for the older subjects [$F(1,24) = 6.6, p < 0.05$].

Additional analyses with respect to this interaction showed that the interaction between display and control integrality was significant only for the older subjects [$F(1,12) = 9.1, p < 0.05$]. Hence, the young subjects' tracking performance was not clearly hampered by incompatibility of integrality. Furthermore, for the young subjects, dual-axis error increased with separated displays [$F(1,12) = 11.2, p < 0.01$], whereas control integrality had no effect.

A Newman-Keuls analysis on the selective effects of display and control integrality for the old subjects, showed that all differences between conditions were significant ($p < 0.01$). This means that the older subjects performed poorest when partial integration involved integration of the *response* component, which was more detrimental than partial integration involving integration of only the *stimulus* component, which in turn was more detrimental than complete integration, whereas no integration at all resulted in optimal dual-tracking performance (Fig. 8.2).

In order to analyze the effects of axis similarity, a 2 (age) × 2 (axis similarity) ANOVA was carried out on the two conditions with completely separated tracking axes. Not surprisingly (with respect to the previously discussed data), no main effect of age was found. Also similarity of tracking axes showed no significant effect, although increased subtask similarity tended to be more detrimental for the older subjects. The age × axis similarity interaction, however, did not reach significance (p = 0.07). Therefore, the data only give an indication that older people may have difficulties when two independent subtasks become more similar only at a superficial level.

Correlations between axes

A 2 (age) × (display integrality) × 2 (control integrality) ANOVA on the *absolute* correlations (see § 8.2.3 Experimental blocks) in the four compatibility of integrality conditions demonstrated a main effect of age [$F(1,24) = 10.3, p < 0.01$]. Mean absolute correlations for the older (0.11) were higher than for the young subjects (0.08). This demonstrates a higher susceptibility for cross talk for the older subjects (Fig. 8.3). A main effect of display integrality demonstrated that separation of the tracking axes on the display made the subject group as a whole more susceptible to cross talk than to display integration [$F(1,24) = 14.1, p < 0.005$]. Such a main effect was not present for control integrality.

In addition, the old subjects tended to higher cross talk when the controls were integrated, whereas the young subjects tended to higher cross talk when the controls were separated [$F(1,24)$ = 3.34, $p=0.08$]. Such an interaction with age was not found for display integrality. Hence, only *response* integration tended to increase cross talk in the old subjects, whereas in the young subjects it tended to decrease cross talk.

Fig. 8.3 also shows a significant interaction between display integrality and control integrality [$F(1,24)$ = 4.7, $p<0.05$], which was apparent for both groups. However, as opposed to the RMS data, this interaction was only partially constituent with a compatibility of integrality effect. Axis cross talk was high only when the *response* component was integrated and display integrality did not match. In case of separated controls, such a compatibility of integrality effect was not seen. In general, for both groups, effects of compatibility of integrality on cross talk were seen only when partial integration involved integration of the response component.
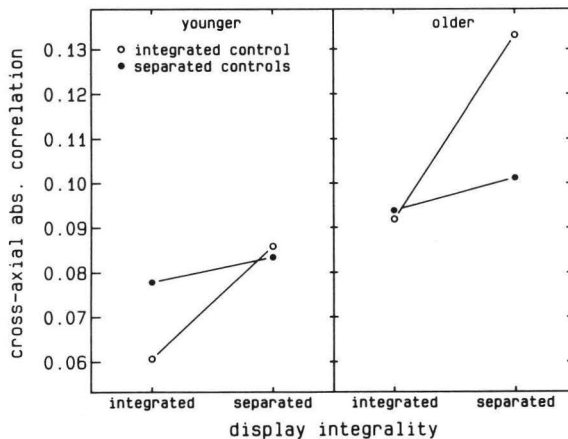

Fig. 8.3 Mean absolute correlations (cross talk) between perpendicular tracking axes for young and older subjects, as affected by display integrality and control integrality.

In the condition with a high degree of axis similarity (i.e., tracking axes in line), correlations for the young subjects and the older subjects were 0.08 (*SD* 0.032) and 0.13 (*SD* 0.037), respectively. These significant correlations ($p<0.001$) demonstrated cross talk between subtasks. Furthermore, the positive sign of these correlations indicate that compensatory tracking was less adequate when pointers were located at the *same* side of the targets. Also, the difference between age groups was significant [$F(1,24)$ = 12.9, $p<0.005$]. This means that in this condition with superficially similar subtasks, the older subjects again were more susceptible to cross talk than their younger counterparts.

An analysis of the effect of axis similarity in the two conditions with completely separated tracking axes (perpendicular versus in line) would not make sense, since the nature of the correlations in these conditions (absolute versus normal) was different. However, the relatively high correlations only for the older subjects with similar tracking axes suggests a selective age effect of axis similarity.

8.4 Discussion

The aim of the present experiment was to investigate age effects in pure dual-task performance (tracking error and cross talk), as affected by two kinds of incoherent (representational) similarity between subtasks: incompatibility of similarity (partial integration) and axis similarity. If a dual task consists of two incoherent (uncorrelated) subtasks, similarity in a dual task may be assumed to increase mapping requirements in task performance. Therefore, for the present uncorrelated tracking tasks, it was expected that age effects will increase when there is incompatibility between display and control integration or when axis similarity of the constituent tasks is increased.

Dual-task tracking performance of the young subjects (rated by RMS tracking error) was not significantly affected by the integrality manipulations. For the old subjects, however, tracking performance was degraded substantially when compatibility of integrality was low—that is, when display integrality and control integrality of the dual tracking task did not match. For the young subjects, this was not the case. Partial integration involving integration of only the response component was most detrimental for the older subjects' tracking performance, followed by partial integration involving integration of only the stimulus component, complete integration, and no integration at all, in that order. These results indicate that apart from partial integration, older people may also suffer from complete integration, without incompatibility between stimulus and response components. The predomination of display integrality above control integrality for the *young* subjects (i.e., control integrality had no substantial effect whereas display integration led to less tracking error than display separation) found in the present experiment is in accordance with the data of Fracker and Wickens (1989), concerning identical tracking dynamics on two axes, and of Chernikoff and LeMay (1963), concerning position dynamics on two axes. Both studies were based on only young subjects. Also the absence of a compatibility of integrality effect links up with the data of Fracker and Wickens (1989). In their most simple condition of tracking dynamics (complete *velocity control*), their data concerning display integrality × control integrality show an almost identical pattern, but the interaction also is not reported significant. The same counts for the study of Chernikoff and LeMay (1963) with respect to their data in the condition with complete position dynamics. Therefore, the tracking error data for the

young subjects in the present experiment may be regarded as a replication of former data.

When people fail to make the proper mapping operations, confusion may result and the constituent subtasks may interfere and mutually disrupt one another. For the four integrality conditions, cross talk was rated by calculating the absolute between-axes correlations in the error signal. Cross talk was found to be higher for the older subjects. This age effect was not conclusively affected by task conditions; the old subjects tended to higher cross talk when the controls were integrated, whereras the young subjects tended to be affected by higher cross talk when the controls were separated. For both age groups, cross talk was increased by partial integration only when it involved integration of the response component. Such a compatibility of integrality effect was not found when the stimulus component was integrated. Furthermore, and in accordance with the error data of the young subjects, separation of the tracking axes on the display led to greater cross talk than display integration did.

In summary: When partial integration was limited to the response part of the task, the incompatibility of integrality effect was seen over both measured dual-task variables. With respect to cross talk, partial integration was not detrimental for the older subjects (nor for the younger ones) when it involved only the stimulus component. Problems of older subjects are maximal when partial integration is confined to integration of only the response parts of the dual task. In this situation, their dual-task performance will be affected by cross talk. In that case, separate perceptual information has to be combined to one radial representation, based on which integrated motor actions have to be performed. Considering these results, the question remains open as to what characterized the older subjects' poor dual-axis tracking performance when partial integration involved integration of the display component. In this connection, it should be noted that movements directed to the wrong tracking axis are irrelevant for the amount of error at this axis, though it may be supposed to decrease the effectivity of task performance.

In case of increasing incoherent similarity, operationalized by similar tracking dimensions, it was also assumed that task demands involving the selective mapping of stimuli, processing operations, and responses would increase. When separate and unrelated subtasks are similar at a superficial level, they may become more susceptible to mutual disruption. Performance of older people in particular was expected to be hampered when subtasks were made more similar only at a superficial level. With respect to RMS tracking performance, only the older subjects' performance tended to be hampered by increased task similarity ($p = 0.07$). With reference to axis cross talk, both age groups responded inadequately when the pointers were at the same side of the targets. This was indicated by the *positive* sign of cross axial correlations. Moreover, these correlations were higher for the old subjects. When the pointers of the constituent tasks

are located at the same side of the targets, the subtask stimuli may be regarded superficially maximally similar. Therefore, it can be concluded that for both age groups, and especially the older age group, task performance is hampered by cross talk in information processing when unrelated subtasks become more similar at only a superficial level (incoherent similarity).

The present results cannot be captured by usual interpretations of multiple resources theory (e.g., Gopher and Sanders, 1984; Navon and Gopher, 1979; Wickens, 1984), which assume that, as long as the same global resources are involved, task performance should depend only on resource demands, i.e., on task difficulty. Each of the present task conditions depended on the same resources and the subtasks were adjusted to one difficulty level. Hence, the present data are far too specific to be explained by the degree to which subtasks compete for resources, or the possibility that older subjects suffer more from resource competition. Furthermore, on the basis of scientific parsimony, it cannot be justified to postulate another resource for each specific kind of task interference that may be found. Therefore, the present results, and other results indicating specific interference effects (e.g., Duncan, 1979; Klapp, 1979; McLeod, 1977; Peters, 1977), can only be explained by conceptualizations in which concrete coherent and incoherent similarities are taken into account (see Chapters 2-4 of the present thesis). Therefore, the conclusion that older people are extra penalized when subtasks are only partially integrated, especially if this only involves the response component, or when independent subtasks have a high representational similarity, may only be explained on the basis of more minute information processes.

The present results are compatible with the slowing-complexity hypothesis: the older subjects, on balance, showed slower information processing abilities in single-task performance, and in the conditions with minor mapping complexity, age-related differences were mostly absent. This is in accordance with the slowing-complexity hypothesis as far as it is stated that general slowing causes age effects to increase with overall task complexity (Cerella et al., 1980; McDowd and Craik, 1988; Salthouse, 1982). It should be pointed out, however, that in dual tasks, overall task complexity is not determined solely by the summed properties of the constituent tasks, but also by the *relations* between these subtasks. Accordingly, the dual-task situation as a whole, is not equal to the sum of its constituent parts. The difference between the whole and the sum of part-tasks may affect *a priori* age effects. In the present experiment, in which *a priori* differences in single-task difficulty were eliminated, support of the slowing-complexity hypothesis was completely determined by these emergent complexities.

Previously mentioned results (Korteling, 1991), have suggested that one form of similarity (subtask synchronization), that *decreased* overall task difficulty may also amplify the magnitude of age effects in a dual task. This means that emergent characteristics of dual tasks may have a considerable effect on age-related differences in dual-task

performance, which cannot be accounted for by the slowing-complexity hypothesis. The possible effects of these kinds of characteristics, have not yet been extensively investigated. Moreover, the slowing-complexity hypothesis is not very specific with reference to the underlying factors determining dual-task complexity. Consequently it is possible that specific relations between subtasks (i.e. similarities) may be difficult for the older person in particular to handle.

The relatively high cross-axial correlations (irrespective of task conditions), and the higher sensitivity of the older subjects to the similarity manipulations, indicate that with increasing age it may become more difficult to keep simultaneous processing operations, or mechanisms (involved in attention, perception, information processing, and action) separate. It may therefore be supposed that the older subjects were relatively susceptible to interference between subtasks that were dependent on linked or corresponding cerebral units. This means that the present results are in support of the idea that with increasing age, the "functional distance" between active brain structures decreases (Kinsbourne, 1980). However, as has been argumented before, the specific effects of similarity within the same visual, spatial, and motor domain indicate that these processes take place at a finer level of cerebral organization than was previously conjectured.

The poor isolation of the older subjects' active processing structures may be well explained by the presently known neuronal changes with increasing age (see Bondareff, 1985 for a review). Aging-related neuronal reductions in the cerebral cortex—which may be a result of learning and should not necessarily be conceived as degeneration—most markedly affects the external and internal granular layers (layers 2 and 4). In these layers short axoned cells, with a profuse dendritic tree and mainly intra-cortical projections, contribute to the integration and differentiation of processing activity (Brody and Vijayashankar, 1977; Shefer, 1973). A reduction in the number of this kind of neuronal units or connections probably decreases the availability of functionally separated neuronal circuits. Because of this scarcity the system is forced to share common channels for different operations. This may be the basis of interference and cross talk of simultaneous processing operations. Aging-related granular cell decrease may also hamper coherence detection and limit the realization of coherent processing activity between corresponding brain structures. Hence granular cell decrease may also explain previously discussed results indicating that older subjects may benefit less from similarity manipulations that increase the subtask coherence, such as subtask synchronization (Korteling, 1991).

The combination of increased cross talk and decreased benefit from stimulus coherence may be explicated by Fig. 8.4. This figure shows one of several possible simple neuronal models, consisting of granular and pyramidal cells, which may account for this paradox.
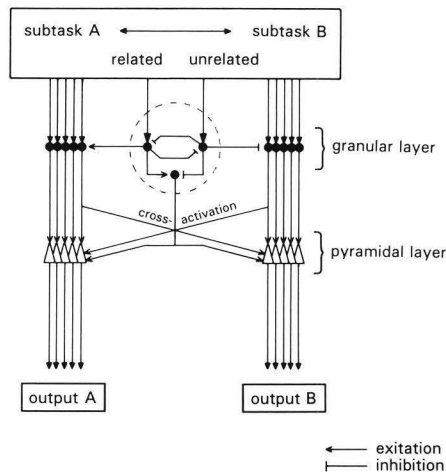
Fig. 8.4 Schematic neuronal network, accounting for increased cross talk and decreased benefits of task coherence in dual tasks, as a consequence of cortical decrease (encircled cluster) of granule (black) in old age.

According to this hypothetical schematic network, which consists of universal components and connections, thresholds of pyramidal cells that are assumed to be simultaneously involved in different tasks (A and B) will be lowered when both tasks are related. This increases the probability that both will simultaneously activate output systems. Moreover, existing cross activity will be stimulated, or released of inhibition. In contrast, when no coherence is detected, the pyramidal cells, activated by task A as well as Task B, will be less stimulated or even inhibited. In this model each kind of decline within the encircled inner cluster of black, short-axoned, cells will disturb parts of this specific activation and inhibition, dependent of task-relatedness.

Of course, many other hypothetic networks of neurons may mediate this kind of selective isolation or correspondence in the activity of neurons.

What may the above findings imply with respect to real world tasks? First, in the area of system ergonomics, integration may not always be an optimal solution to cope with the increasing complexity of modern tasks. This may be especially true in the case of control devices, in which case controls should not have combined functions—for instance, wiper, light and horn in an automobile should not be mounted on one control handle. Furthermore, similarity in design and function of different control and monitoring devices should be avoided. The current development of multi-purpose electronic displays for the presentation of information from different sources may, especially for older people, offer new problems because too much similar information is simultaneously presented at the same location.

Chapter 9

Effects of aging, skill modification, and demand alternation on multiple-task performance

9.1 Introduction

In a wide variety of laboratory experiments, older adults are found to have difficulties in dual-task performance (Broadbent and Gregory, 1965; Brouwer, Waterink, van Wolffelaar, and Rothengatter, 1991; Clark and Knowles, 1973; Craik, 1965; Inglis and Caird, 1963; McDowd, 1986; McDowd and Craik, 1988; Ponds, Brouwer, and van Wolffelaar, 1988; Salthouse, Rogan, and Prill, 1984; Talland, 1962). Since many everyday and occupational activities also involve the performance of simultaneous actions, aging-related decrements in multiple-task capabilities have critical implications for a rapidly growing segment of the population. However, in order to take measures aimed at the design of better adapted and supportive environments, more specific knowledge is needed concerning the task characteristics that produce the age deficits and affect the magnitude of this effect.

A first variable that may affect age-related differences is the amount of attentional capacity required by the task. In this respect, two different modes of information processing are discerned (e.g., Fisk, Ackerman, and Schneider, 1987; Hasher and Zacks, 1979; Logan, 1978; Posner and Snyder, 1975; Schneider and Shiffrin, 1977; Shiffrin and Schneider, 1977, 1984), which mostly are referred to as *automatic* and *controlled* processing (Schneider and Shiffrin, 1977). Automatic processing is fast, parallel, effortless, and not under direct subject control. It usually is regarded as an important contributor to well-developed skilled behavior, but it only develops when tasks are characterized by an invariant relationship between stimuli and responses (consistent mapping). Once learned, automatic processes are difficult to suppress, modify, or ignore; once evoked, automatic processes generally run to completions. In contrast, controlled processing is generally regarded as slow, serial, effortful, subject regulated and needed in situations where responses required to stimuli are inconsistent (varied mapping). Controlled responses are easily modified, suppressed, or ignored.

The performance of most complex tasks typically involves the separate and combined influences of automatic and controlled processes. Hasher and Zacks (1979) postulated that in tasks predominantly consisting of controlled elements, age-effects are large, whereas in tasks that permit a high degree of automatic processing, differences between young and older subjects tend to disappear. However, Fisk, McGee, and Giambra (1988) demonstrated that *in* old age, the degree to which older subjects can acquire new automatic processes (in visual search) declines. They suggested that only previously developed automatic processing may remain effective in old age. In addition, Fisk and Rogers (1991) cite data in the areas of Stroop interference, lexical access, and implicit memory that are compatible with the notion that long-practiced, previously developed processes are unaffected by age (*age-independence*). For example, in an arithmetic Stroop task, Rogers and Fisk (1991) found the same pattern of associative interfering processes across age groups. According to the authors, this suggests that previously well-learned processes do not diminish with age. However, whereas the interference effect decreased with practice for the young subjects no significant decrease in associative interference effects was found for the old subjects. In line with Cohn, Dustman, and Bradford (1984), who found stronger Stroop interference for older subjects, Rogers and Fisk (1991) conclude that older adults have more difficulty suppressing previously well-learned automatic routines.

Related to this, it is an important question whether age-effects occur in *dual-task* skills, which were already well-learned in daily life before old age, and how this is affected by the requirement to modify these components of these skills. With regard to dual tasks, task combinations involving well-trained (automatic) routines typically produce smaller interference effects, than dual tasks which mainly consists of controlled elements. Schneider and Fisk (1982), for instance, showed that dual tasks sometimes even can be performed without noticeable deficit when one of the tasks shows the characteristics of automatic processing. Because previously acquired automatic processes tend to remain effective in old age (e.g., Fisk et al., 1988; Fisk and Rogers, 1991), we thus may expect age-independence or minor age-effects in single tasks as well as in dual tasks when these tasks were well-trained in daily life. However, when well-learned psychomotor skills have to be modified, subjects have to suppress well-learned routines. In these situations, single-task performance, but dual-task performance as well, may be expected to show age effects (e.g., Cohn et al., 1984; Rogers and Fisk, 1991).

Also dual-task variables emerging from the combination or mutual relation of subtasks are supposed to be an important determinant of age differences in dual-task performance. In this connection, it has been suggested that the degree and nature of *similarity* between subtasks (Korteling, 1993; Wickens, 1989, 1992) may be a factor determining the magnitude of age differences in dual-task performance (e.g., Korteling, 1991). Similarity refers to concrete content-specific task characteristics, such as spatial, temporal, syntactic or semantic similarities, similarities in subtask goals, colors, forms, required processing

routines, stimulus-response mappings, or actions (Korteling, 1993). The effects of similarity on time-sharing may act positively and negatively. When similarity refers to coherent or corresponding inputs, processing operations, or actions, or to common or compatible stimulus-response mappings, timing mechanisms, or goals, the integration or coordination of subtasks is facilitated, which may enhance task performance (e.g. Duncan, 1979; Korteling, 1991; Klapp, 1979; Peters, 1977). This is termed *coherent similarity* (Korteling, 1993). It can be argued that many everyday dual tasks, such as oral reading, piano playing, or vehicle control, may entail such a high degree of internal coherence or relatedness that they are easily experienced as single tasks. With reference to positive effects of similarity on age-related differences, Korteling (1991) found that in a simple dual compensatory tracking task, young subjects did not outperform the older subjects, except when the pointers of two tracking tasks made synchronous movements (which made the task easier). Obviously, synchronization of constituent tasks enabled only the young to integrate, or combine, these separated activities. This was termed *skill integration* or *performance integration* (Korteling, 1991, 1993).

However, similarity may also degrade time-sharing efficiency. When similarity only involves *concrete and superficial elements* of the dual task in terms of space, color, or form, while underlying processing routines (e.g., stimulus-response mapping) are incompatible or unrelated (*incoherent similarity*), it will be more difficult to keep the tasks isolated. Subjects may then unintentionally combine the subtasks, such that the constituent tasks will become more susceptible for mutual disruption, cross talk, or interference (e.g., Navon and Miller, 1987). With respect to aging, Korteling (1991) found that in dual-axis tracking, age-effects in terms of tracking error and cross talk, were increased by similarity-based confusions, i.e., incompatibility between stimulus and response integration (*proximity compatibility*, Fracker and Wickens, 1989) and axis similarity.

In conclusion, task characteristics emerging from the relationship between subtasks, i.e., coherent and incoherent similarities among subtasks, may have considerable impact on the magnitude of age differences in dual-task performance. According to Korteling (1993), the decreasing ability of older persons to handle coherent and incoherent similarities, may be caused by deteriorations with regard to combining or integrating related or coherent task elements or isolating unrelated or incoherent task elements. In the present study, these difficulties with the combinatory dual-task aspects were assumed to be related to a suboptimal allocation of attention among subtasks—that is, a decrement in the ability to prioritize the appropriateness of multiple sources of information and shifting attentional emphasis accordingly (see also Craik, 1977; Craik and Simon, 1980)

Another well-known variable that is associated with dual tasks is overall task complexity. In simple perceptual-motor tasks, age-related differences often are found to be small or absent. Otherwise, increasing the complexity of tasks, has been found to enlarge the magnitude of the age effect (e.g., Birren, Woods, and Williams, 1980;

Cerella, 1985; Welford, 1958, 1965, 1977). This idea has been elaborated with the notion that cumulative slowing in successive processing steps causes performance differences between age groups to increase with task complexity, that is, the number of required processing operations (Cerella, 1985; Cerella, Poon, and Williams, 1980; Hale, Myerson, and Wagstaff, 1987; Myerson, Hale, Wagstaff, Poon, and Smith, 1990). Salthouse (1982) suggested that a dual task is nothing more than a complex version of a single task, which necessitates the involvement of more mental operations. This means that observed age effects of complex single tasks and dual tasks are the same in nature. According to Salthouse et al. (1984) and Salthouse (1982) the substantial age-related performance differences in dual tasks may therefore be caused by the mere complexity of these tasks. This notion has been called the *slowing-complexity hypothesis*. In two experiments, McDowd and Craik (1988) tested the hypothesis that age differences in dual-task performance are amplified by an increase in the complexity of the constituent tasks. Although they found highly reliable age decrements in divided attention performance, in terms of both relative and absolute divided attention costs, the magnitude of age differences was not consistently affected by complexity manipulations. Nevertheless in their study, RT performance of the old subjects could be predicted on the basis of younger subjects' performance, without regard to the nature of the task. This means that in this study, the evidence concerning the slowing-complexity hypothesis with respect to dual tasks was equivocal.

The purpose of the present experiment was to examine age-independence in previously well-trained single and dual tasks as affected by the requirement to modify the involved psychomotor routines. In addition, the experiment addressed effects of attention allocation requirements emerging from the relationship among subtasks, i.e., whether subtask demands were constant or alternating in counter-phase.

9.2 Method

9.2.1 Subjects

Two age groups of 12 subjects participated in the experiment, each consisting of 10 males and 2 females. The mean age of the old subjects was 70 years (range 65-74, SD 2.9); the mean age of the young was 27 years (range 21-34, SD 5.3). All subjects were recruited from the community and were compensated monetarily. By frequency distribution control (Christensen, 1977), the subjects were matched on level of education. All subjects reported to be healthy and had normal or corrected-to-normal visual acuity. Mean raw scores of the subject groups on Digit-Symbol Substitution of the Dutch version of the Wechsler Adult Intelligence Scale (WAIS) were 42 for the older subjects and 63 for the young subjects. When these scores were scaled with respect to age, they were not

significantly different. Subjects were paid for their participation. Because the concerned subtasks were very elementary, all subjects were considered experienced with respect to these tasks (> 10000 km driven over the last 5 years). However, total driving experience for the old subjects was significantly higher (mean 75000 km, SD 55000 km) than for the young subjects (mean 55000 km, SD 36000 km).

9.2.2 Apparatus

The experiment was conducted in the driving simulator of the TNO Institute for Perception. Fig. 9.1 gives the basic configuration of this fixed-base driving simulator. The control system has a modular design with three sub-systems.

The *supervisor* computer (COMPAQ 386) with tasks such as communication with both the experimenter and the other sub-systems, the control and monitoring of the experiment, data-storage, etc..

The *vehicle-model* computer (IBM 286) for calculating the instantaneous position (X- and Y-coordinates) and heading-angle (FI) of the simulated vehicle; this vehicle had the dynamic characteristics of a Volvo 240.

The *visual scene* computer (Megatek 944 CGI-system) that generated real-time images with a update rate of 30 Hz.

The subject was seated in a fixed-base mock-up of a Volvo 240 containing all normal controls (steering-wheel, accelerator, gear-shift, brake, etc.). Based on the status of these controls, the vehicle-model computed the consequences in terms of speed and heading changes, in the same way a real vehicle would react to a driver's actions. Feedback of steering forces was given to the driver by means of an electrical torque engine, and of sound by a electronic sound-generator (noise of engine, wind, and tires). The instantaneous position and heading-angle were transmitted via the supervisor to the visual-scene computer. The CGI-system computed the corresponding visual scene as seen from the driver with a resolution of 1024 × 1024 pixels in full color (24 bit RGB). This image was projected on a screen in front of the mock-up by means of a high-resolution BARCO-GRAPHICS 800 projector with a display rate of 60 Hz. The horizontal and vertical visual angles of the image on the screen were 40 degr. This resulted in a resolution of 26 pix./degr..
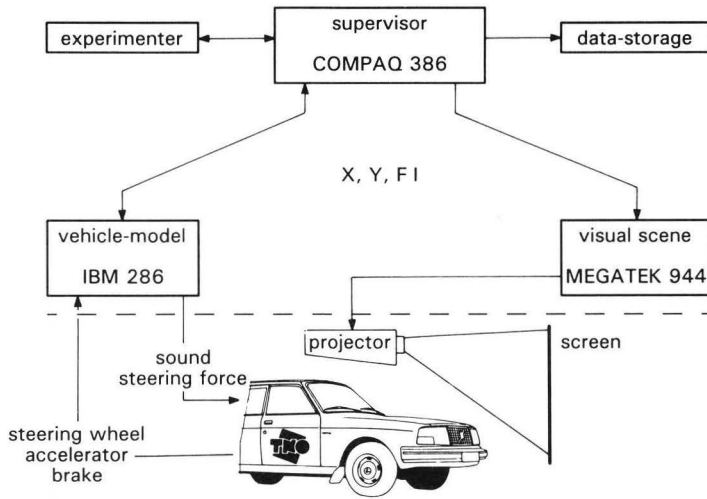
Fig. 9.1 Basic configuration of the TNO driving simulator.

9.2.3 Experimental tasks

In the TNO driving simulator, subjects had to perform a steering task and a car-following task on a straight road. In the dual-task conditions, the steering task was combined with the car-following task. Verwey (1991) studied experienced and inexperienced drivers, driving an instrumented car, in a number of driving situations while performing secondary tasks. He found that an auditory addition (cognitive) task could be performed in all situations by experienced drivers without affecting driving performance. This suggests that in experienced drivers, many aspects of the driving task are automated. In steering a car, the relationship between lane position/heading and required steering actions on normal roads is consistent and the frequency of stimulus-response sequences is high; the "steering action rate" during normal driving on a motorway and a rural road is about 30 times per minute (Verwey, 1991). Therefore, for experienced drivers, this low-level component of driving may be supposed to require minimal attention. In car-following, the range of acceptable distances is less strict and perceptual cues are less precise than in steering. In relation to this, Verwey (1991) found that the frequency of gas-pedal usage is considerably lower (motorway 0.14 times per minute, rural road 7 times per minute). Moreover, the car-following task in the present experiment differed from normal driving in car-following situations with reference to its strict performance criterion. Therefore, the degree of automaticity of task components in the present car-following task may be supposed lower than in the steering task.

Fig. 9.2 shows the basic characteristics of the image as seen by the driver sitting in the TNO driving simulator.
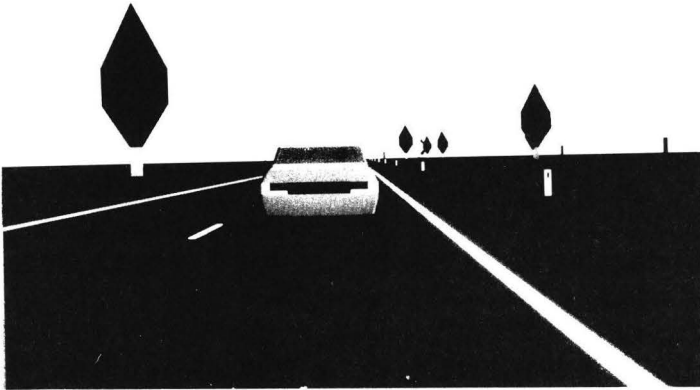

Fig. 9.2 The outside view seen from the driver's position.

Steering task

In the driving simulator subjects drove 15 m behind a lead car on the right lane of a straight freeway (lane width: 360 cm). The transmission was always in the third gear and driving speeds of both cars were fixed at 80 km/h. The lead car drove exactly in the middle of the lane. Subjects were requested to keep their vehicle in the middle of their lane as well as possible, right behind the lead car. Based on a forcing function simulating windgusts (see section "disturbance inputs"), the course of the vehicle was varied such that subjects had to make compensatory steering movements in order to keep their vehicle in the middle of the lane. Performance in the steering (sub)task was measured by calculating the standard deviation of the vehicle's lateral position on the road.

Car-following task

In this task, subjects followed a lead car that continuously changed driving speed. The lateral position of both cars was fixed; both cars drove on the middle of the right lane. Subjects were requested to maintain a distance of 15 m between both cars. Because this aim is rather ambiguous, subjects were assisted by a dark bar, projected 15 m in front of their car on the road. When the near end of the bar was between the back wheels of the lead car, the inter-vehicle distance was exactly 15 m. Again, the speed of the lead car

was varied by a forcing function. Subjects only could use the gas pedal in order to compensate for the resulting variations in inter-vehicle distance. The transmission was again in the third gear and the car-following task did not require gear changes. Mean speed of the lead car was always 80 km/h. Performance in the car-following (sub)task was rated by calculating the standard deviation of the inter-vehicle distance.

Disturbance inputs

In the steering and car-following task, respectively, course of the vehicle and driving speed were varied by the same random band-limited (frequency < 0.4 Hz) pink noise forcing function. The amplitudes of this function were set such that, subjectively, both tasks were equally difficult. With respect to lateral position on the road, this resulted in a SD of 36 cm (range: 94 right - 120 left). With respect to driving speed of the lead car, this resulted in a SD of 5.5 km/h (range: 62-94). The forcing function consisted of 10000 points that were computed before the experiment. To allow continuous transgression when the end was reached, the beginning and the end of the forcing function were adjusted. For each experimental trial, the starting points within the forcing function were chosen randomly.

9.2.4 Independent variables

Both tasks were carried out under single- and under dual-task conditions. This resulted in two single tasks (as described above) and one dual task (steering combined with car-following).

In order to evaluate effects of the degree to which a task required modification of previously well-developed psychomotor routines, the car-following task was performed under two conditions of suppression. In the *normal polarity* condition, the gas pedal functioned as usual: pushing resulted in acceleration and releasing resulted in deceleration. In the *reversed polarity* condition, the output signal of the gas pedal was inverted, such that pushing this pedal resulted in slower driving, whereas releasing resulted in acceleration. The relationship between the extent of gas pedal displacement and resulting deceleration, corresponded to pedal displacement and resulting acceleration of the normal gas pedal. Since in this reversed polarity condition everything except the reversed stimulus-response relationship was equal to normal gas pedal functioning, the subjects were forced to suppress their usual way of responding during car following. This means that the *complexity* (not the difficulty or demand, see Navon and Gopher, 1979) of the inverted polarity condition was identical to the normal polarity condition.

There was no condition with inverted steering wheel functioning. When, in pilot studies, the polarity of the steering wheel output was reversed, many subjects could not perform the task. They often drove into the field and sometimes could even not find

their way back to the road, which makes the task qualitatively different. Conceivably, this task was automated to such a high degree that subjects could not suppress and modify previously acquired routines in this task during this experiment.

All single- and dual-task configurations were performed in two conditions. In one condition, demand of the subtasks was constant and in the other condition, demand was varied by changing the amplitude of the disturbance signal between two values, ten times *within* each trial. In the dual-task conditions, this demand was varied in a consistent (coherent) manner—that is, demand *alternated* between subtasks *in counter-phase*. When one subtask became more demanding, the other simultaneously became less demanding. The mean amplitude of the disturbance signal in constant or varying demand conditions was always equal. Old and young subjects differ in the degree to which they are able to utilize or handle combinatory dual-task aspects (Korteling, 1991, 1993), which may be related to a suboptimal allocation of attention among subtasks (e.g., Craik, 1977). Therefore, it was expected that older subjects would be less proficient to allocate attention and control behavior appropriately relative to the consistently changing demand levels of the subtasks.

The two fixed levels between which demand could be varied within a subtask were based on a multiplication of the amplitudes of the disturbance inputs with 0.6 (low demand) or with 1.4 (high demand). With respect to lateral position on the road, this resulted in a SD of 22 cm (range: 56 right - 72 left), and of 51 cm (range: 150 right -168 left) in the low-demand intervals within a trial and high-demand intervals within a trial, respectively. With respect to driving speed of the lead car, this resulted in a SD of 3.3 km/h (range: 69-89) or of 8.8 km/h (range 51-103) in the easy and difficult intervals, respectively. In pilot studies, it appeared that steering and car-following performance increased linearly with task demand within the range of 0.6-1.4 in which demand was varied. Hence, within this range, effects related to elementary perceptual or motor limitations (e.g., thresholds) were not expected. Moreover, the proportion of error reduction, and thereby the attentional load, increased with the amplitude of the disturbance signal. Also the present data showed that the amount of error reduction [(input SD-output SD)/input SD] increased with disturbance amplitude. For the steering task the proportions of error reduction were: 0.27, 0.39, 0.47 for low, constant/intermediate, and high disturbance amplitude, respectively. A similar increasing proportionality of movement reduction was found for the car-following task—i.e., 0.55, 0.69, 0.75, respectively. Differences between groups or single and dual tasks with respect to these increasing proportions were marginal. Accordingly, for both age groups, increasing disturbance amplitude produced increasing attentional demands.

The design is presented in Table 9.1.

Table 9.1 A representation of the experimental design. In the dual-task conditions, the steering task was combined with one of the two Pedal Polarity conditions of the car-following task.

		alternating demand		constant demand	
		single	dual	single	dual
steering task	normal polarity				
car-following task	normal polarity				
	reversed polarity				

9.2.5 Data collection

Lateral and/or longitudinal positions were sampled and stored for analysis with 30 Hz. Each trial, this was measured in 10 intervals in which the amplitude of the disturbance signal was constant. These ten periods were connected by 10 "transition periods". In the experimental conditions, a trial was preceded by a warm-up period. Only in the conditions with alternating task demand were the transition periods actually used to vary the amplitude of the disturbance signal. In the warm-up period and in the transition periods, no data were collected. The 10 measurement intervals in the experimental trials took 18 s each.

9.2.6 Procedure

Subjects participated during a one-day session. Each day two subjects were tested such that one subject relaxed while the other performed one block of single- or dual-task trials. Subjects were seated in the simulator room. The experimenter was situated in an adjacent room from where he could communicate with the subjects via an intercom.

Practice blocks

The practice blocks started with a short introduction about the nature of the experiment. Subjects were instructed to devote the same amount of total effort to performance regardless of the number of subtasks required. On dual-task trials, subjects were instructed to keep performance on both subtasks as equal to each other as possible. After the general instructions, the subjects practiced in two single-task blocks and two

dual-task blocks. During practice, a dual-task block was always preceded by a single-task block. In order to control for sequencing effects, however, the order of conditions within blocks was counterbalanced between groups. In a single-task practice block, each single-task condition was performed once. Hence, a single-task practice block was comprised of six trials, that is steering in two conditions of Demand Alternation and car-following in four conditions, created by the factorial combination of Pedal Polarity with Demand Alternation.

Like single-task practice, for each dual-task condition one trial per block was done. This resulted in four trials per block, i.e., two conditions of Pedal Polarity × two conditions of Demand Alternation.

Since transition periods lasted 3 s and "measurement intervals" lasted 9 s, a practice trial took 120 s ($10 \times 3 + 10 \times 9$). Trials were interrupted by a 20 s rest period.

Experimental blocks

The experimental blocks differed in three respects from the practice blocks: 1) the sequence of single and dual tasks was counterbalanced, 2) each trial started with a warming-up period of 15 s, and 3) the measurement intervals lasted 18 s instead of 9 s. Therefore all trials lasted 225 s ($15 + 10 \times 3 + 10 \times 18$). For the rest, everything was equal, i.e., four experimental blocks (two dual-task blocks and two single-task blocks), six trials per single-task block, and four trials per dual-task block. Again, all trials were interrupted by a 20 s rest period, except in the middle of a block, when a pause of one minute was given. After trials, no feedback was given.

9.2.7 Data analysis

Data were analyzed with ANOVA in which subjects were nested under the two age groups. In order to control for effects of age differences already present under single-task conditions, for each dual-task condition, the raw data indicating dual-task performance had to be adjusted (Somberg and Salthouse, 1982). Therefore, dual-task performance was expressed as the difference between the measured dual- and single-task standard deviations divided by the single-task standard deviations, i.e., under the comparable conditions (e.g., McDowd, 1986). In this manner, eventual age-related differences in dual-task performance could not be confounded by initial differences in single-task steering and car-following abilities.

9.3 Results

9.3.1 Single tasks

Steering task

Single-task steering performance was analyzed in a 2 (Age) × 2 (Demand Variation) ANOVA. The standard deviation of lateral position was 23 cm for the young subjects and 21 cm for their older counterparts. This difference was not significant, which corroborates the hypothesis that in skilled tasks, which are previously extensively practiced, age-related performance differences typically do not occur (Fisk et al., 1988; Fisk and Rogers, 1991).

There was no main effect of Demand Variation, nor was there an Age × Demand Variation interaction. This means that the *mean* task difficulty of the condition with constant disturbance amplitude and variable amplitude was equal. Hence, the requirement to *adapt* behavior (speed amplitude of compensatory steering movements) to the changing task demands (speed amplitude of disturbance movements) was not found to be difficult for both age groups.

Car-following task

Single-task car-following performance was analyzed in a 2 (Age) × 2 (Novelty) × 2 (Demand Variation) ANOVA. As can be seen in Fig. 9.3, the older subjects performed poorer than the young subjects, $F(1,22) = 16.3$, $p < 0.001$.
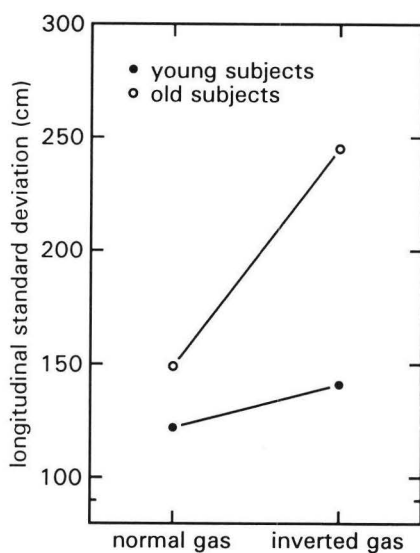
Fig. 9.3 Single-task car-following performance of both age groups, as affected by Polarity of the gas pedal.

There was also a significant effect of Pedal Polarity, $F(1,22) = 27.6$, $p < 0.0005$, which interacted with age, $F(1,22) = 12.3$, $p < 0.005$). Separate analyses with respect to this interaction showed that the difference between old and young subjects was not significant in the normal condition and that the effect of polarity reversal was not significant for the young subjects. Hence, the age effect can be explained almost completely by the poor performance of the older subjects in the condition with inverted polarity of the gas pedal. This demonstrates an age-effect only when a previously well-learned response tendency has to be suppressed.

The data are clearly not in accordance with the slowing-complexity hypothesis, because the objective stimulus-response relationship of car-following with inverted gas pedal functioning and normal gas pedal functioning, given the same task situation, may be considered as equally complex. Investigators usually consider performance levels of young subjects as a valid index for task difficulty/complexity, provided that both subject groups use the same processing mechanisms to perform the task (e.g., Cerella, 1985; McDowd and Craik, 1988; Salthouse, 1988). Therefore this conclusion is corroborated by the unaffected performance levels of the young subjects under both Pedal Polarity conditions, which means that—after the training sessions— these tasks were about equally difficult for the young.

Again, there was no main effect of Demand Variation, nor was there an Age × Demand Variation interaction, which means that the *mean* task difficulty of the condition with constant disturbance gain and variable gain was equal for both task conditions and for both groups. Considering the same results with respect to the steering task, older subjects appear not to be hampered by demand fluctuations caused by gain variations in the present single tasks.

9.3.2 Dual tasks

Steering performance

Since dual-task performance was expressed as the degree of performance variation relative to single-task performance under the same conditions, these *relative* performance data were termed *dual-task costs*. For steering performance, these dual-task costs were analyzed in a 2 (Age) × 2 (Pedal Polarity) × 2 (Demand Alternation) ANOVA. In this analysis, Pedal Polarity referred to whether or not the steering task was *combined* with the normal car-following task, with which all subjects were familiar, *vs* the car-following task with reversed polarity of the gas pedal, which may be supposed to be minimally practiced before the experiment.

This analysis did not show a significant effect of Age ($p < 0.20$) or of Demand Alternation. However, there was a significant effect of Pedal Polarity, $F(1,22) = 7.8$, $p < 0.05$, which interacted with Age, $F(1,22) = 7.8$, $p < 0.05$. Fig. 9.4 shows that only the older subjects were hampered by the extra car-following task when this task was not practiced before old age. Therefore, the data substantiate the hypothesis that in a dual task, task performance becomes poorer when at least one of the subtasks requires modification of a well-learned psychomotor routine. The results of the young subjects show that both conditions of the factor Pedal Polarity were equally difficult for them. In that case, the slowing-complexity hypothesis would not predict an effect of these conditions for the older subjects either. Therefore the Age × Pedal Polarity interaction is not predicted by, and thus incompatible with, the slowing-complexity hypothesis.
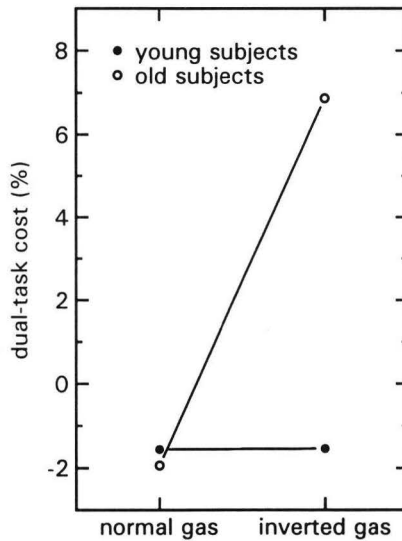
Fig. 9.4 Dual-task costs on steering performance of both age groups, as affected by Polarity of the gas pedal.

Car-following performance

With respect to car-following performance, dual-task costs were analyzed in a 2 (Age) × 2 (Pedal Polarity) × 2 (Demand Alternation) ANOVA. This analysis provided no main or interaction effects. Although, both age groups were clearly hampered by the dual-task requirements relative to their single-task performances (24 % performance deterioration), this effect was not different for age groups and was unaffected by Pedal Polarity and Demand Alternation. Although we saw that the requirement to modify a well-learned routine was more deleterious for the older subjects with respect to single-task performance, this aging-related modification problem does not show in the dual-task costs of the to-be-modified task when it is combined with another well-learned task.

9.3.3 Training or fatigue effects

In pilot studies, it was determined how much practice was required in order to reach a stable task performance for both age groups. This amount of training was described in the procedure section. In order to check if this amount indeed had been sufficient ANOVA's were carried out in which block number was incorporated as a variable.

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Steering performance

With respect to steering performance a 2 (Age) × 2 (Demand Alternation) × 2 (Block Number) ANOVA on the *single*-task data showed a significant effect of Block Number, $F(1,22) = 4.2$, $p < 0.05$. However, this effect was contrary to a training effect; subjects performed worse in the second experimental block. Presumably, this was a fatigue effect. This effect was equal for both groups, but it interacted with Demand Alternation, $F(1,22) = 16.6$, $p < 0.001$. Fig. 9.5 shows that the fatigue effect was only evident in the conditions with alternating task demand. The lower steering performance in the second block only for the conditions with alternating task demand is difficult to explain, and may be a consequence of chance capitalization.
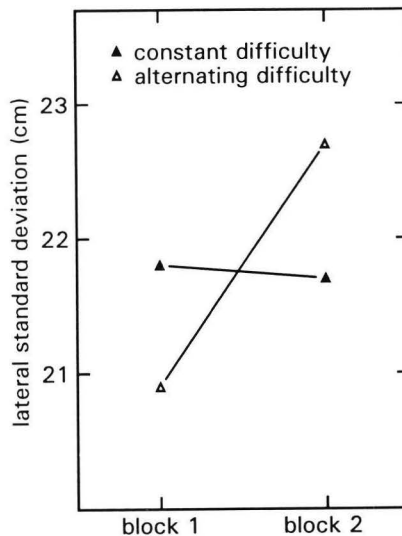
Fig. 9.5 Single-task steering performance of the subject group as a whole, as affected by Demand Alternation and Block Number.

A 2 (Age) × 2 (Pedal Polarity) × 2 (Demand Alternation) × 2 (Block Number) ANOVA on dual-task costs in steering performance did not show any significant main or interaction effects of Block Number.

In conclusion, in accordance with the idea that the steering task could was a thoroughly trained, highly "automated" task, subjects did not show training effects.

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Car-following performance

With respect to *single*-task car-following performance, training or fatigue effects were analyzed in a 2 (Age) × 2 (Pedal Polarity) × 2 (Demand Alternation) × 2 (Block number). This ANOVA only showed one marginal interaction of Block number with Pedal Polarity (p < 0.10). This interaction suggests that subjects tended to deteriorated task performance with increasing practice when Pedal Polarity was normal, while task performance tended to improve with practice when the gas pedal was inverted (Fig. 9.6). This indicates that with respect to the atypical gas response, subjects may not have been completely trained. This effect, however, is small and not very reliable.

As was the case for steering performance, a 2 (Age) × 2 (Pedal Polarity) × 2 (Demand Alternation) × 2 (Block number) ANOVA on dual-task costs in car-following performance did not show any significant main or interaction effects of Block number.
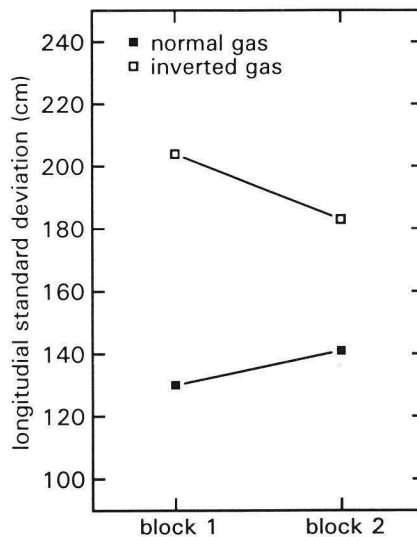
Fig. 9.6 Single-task car-following performance of the subject group as a whole, as affected by Polarity of the gas pedal and Block Number.

In summary, there was only one small training effect in single-task performance, suggesting that subjects were not completely trained with respect to the car-following task with inverted pedal polarity. Furthermore, there were no age-related differences, neither in sequential effects nor in dual-task performance.

9.4 Discussion

With respect to the development of skilled performance, Fisk et al. (1988) and Fisk and Rogers (1991) made a distinction between the development of well-learned (automatic) skills and their use. Only well-learned kills developed prior to old age, may remain effective when old age is reached, whereas the degree to which older subjects can acquire *new* automatic processes declines (Fisk et al., 1988; Fisk, Rogers, and Giambra, 1990). In addition, Rogers and Fisk (1991) have demonstrated that older adults are impaired in their ability to modify such a previously well-learned automatic skill, which requires acquisition of new processes and inhibition of automatic routines as well.

Although it cannot be claimed that the present study included fully automatic tasks in the perceptual-motor domain (meeting the criteria for automaticity mentioned in the introduction) on balance, the results in this study were consistent with these findings. Age-decrements did not appear when well-learned single-task skills were previously acquired. That is, for steering and car-following with normal-polarity gas control, age-effects were absent. However, car-following with inverted polarity of the gas pedal produced a substantial age effect. Apparently, the fact that a well-learned skill has to be modified during the experiment does not affect performance when subjects are young, whereas in old age, it makes a substantial difference. These single-task results indicate that previously developed well-learned psychomotor skills do not diminish with age but also are difficult to modify. In the present experiment, this skill modification involved not only the acquisition of a new skill to correctly utilize the new pedal polarity, but also required the "unlearning" of how gas pedals usually work—that is, the inhibition of a well-learned psychomotor routine. This means that the present single-task results substantiate the results concerning the inhibition of well-learned routines of Rogers and Fisk (1991), which were based on a more cognitive task, i.e., an arithmetic Stroop task.

The slowing-complexity hypothesis predicts that the magnitude of age-differences is proportional to the complexity of the task (where complexity is usually indexed by the young subjects' mean performance). This means that the effect of pedal polarity on the older subjects was in conflict with the slowing-complexity hypothesis, which would not predict an age-difference in the car-following condition because the young subjects were not hampered by reversal of gas pedal functioning.

Also, in the dual-task conditions, no age-effects were found when both well-learned subtasks were performed in the familiar way.

An age effect was only found when gas pedal polarity was inverted. Therefore, the dual-task data also show that for older subjects, task performance may become relatively poor when skill-modification is required. However, the age-effect was only found in the steering task—that is the subtask that had not to be modified. Presumably, older subjects tend to devote relatively much attention to the subtask requiring skill modification. When well-learned psychomotor routines that have to be modified are conceived as previously

untrained skills acquired during the experiment, this finding is compatible with the results of Fisk et al. (1988) concerning single-task performance. In addition, with regard to divided attention performance in a driving simulator, Brouwer et al. (1991) also found an age-related dual-task deficit only in lane tracking (previously acquired), when this task was combined with a visual analysis task (performed only during the experiment), for which such an effect remained absent. In conclusion, next to the single-task results, also the dual-task results, concerning skill modification, are in line with results based on other operationalizations and task configurations.

Modification of well-learned skills requires inhibition of automatic psychomotor routines. This is one of the most important aspects of *behavior organization*, which is a function associated with the prefrontal areas (e.g., Luria, 1973). Prefrontal damage, for example, is the most prominent cause of perseveration of automatisms and routine actions (e.g., Fuster, 1980). Therefore, the data of the present study as well other data pointing at a declining ability to suppress well-learned routines (Fisk and Rogers, 1991; Cohn et al., 1984; Comalli, Wapner, and Werner, 1962) is compatible with existing neuropsychological (Albert and Kaplan, 1980; Fuster, 1980) and neuropathological (e.g., Scheibel and Scheibel, 1975) evidence for a disproportional decline of the prefrontal system with increasing age.

With respect to dual-task steering performance, the young subjects' task performance showed that both conditions of gas pedal polarity were equally complex. Therefore, the age × pedal polarity interaction, showing an age deterioration only when steering was combined with the car-following situation requiring skill modification, is not predicted by, and thus incompatible with, the slowing-complexity hypothesis.

With respect to car-following, both age groups were equally hampered by the dual-task requirements to a relatively high degree (24% performance deterioration relative to single-task performance). This effect was unaffected by pedal polarity and demand alternation. When car-following with an inverted gas pedal is conceived as more controlled than the steering with normal polarity of the steering wheel, this finding is compatible with results from Schneider and Fisk (1982) with student subjects, indicating that controlled processes are more easily disrupted by simultaneous automated processes than *vice versa*. Now it may be concluded that the tendency to "*waste controlled resources on automatic processing tasks*" seems not to be different for non-students or for older subjects. Furthermore, the negative effect of an automated task on a controlled task is not affected by age, nor by whether or not the latter task has to be modified. Negative effects of age only seem to be limited to the smaller effects in the previously well-learned task performed in combination with a novel controlled task.

It has been demonstrated that age differences are increased by task variables that emerge from the combination or mutual relation of subtasks (Korteling, 1991, 1993). This may be caused by deteriorations with regard to combining or integrating related or coherent task elements or isolating unrelated or incoherent task elements (Korteling,

1993). It was hypothized that this problem is related to a decrement in the ability to prioritize the appropriateness of multiple sources of information and shifting attentional emphasis accordingly. In this connection, the present experiment aimed at effects determined by whether or not the demand levels of subtasks were alternating in counter-phase, that is, when one subtask became more demanding, the other became to the same degree less demanding and *vice versa*. It was expected that old and young subjects would differ in the degree to which they are capable to sequentially distribute attention in proportion to the covarying demand of the subtasks. The requirement to shift attentional emphasis, however, did not affect task performance in the dual-task conditions. This means that conditions with demand variation were not more difficult or more demanding than conditions with constant demand (provided that the average task demand over both conditions was the same). Apparently, the older subjects were as able as the young subjects to allocate attention appropriately according to the relative subtask demands. This absence of attentional emphasis effects suggests that age effects of emergent task characteristics do not include a deteriorated ability to distribute attention properly in proportion to the varying demands of subtasks.

This conclusion, however, can be refined. Craik (1986) and Craik and Bosman (1992) claim that in memory research, age effects usually are the greatest when subjects cannot rely on environmental support. According to Craik and Bosman (1992), age-effects often disappear when the event itself and its accompanying context are more effective at inducing optimal mental processes, such that there is less need for internally-generated processes to perform the task. In this connection, the absence of (counterphase) demand alternation effects suggests that this emergent variable probably was effectively imposed and supported by the task as a whole. In other words: self-initiated processes may not have played a significant role in the present experiment. With respect to attention allocation between subtasks in dual-task situations, the present results suggest that also in perceptual-motor tasks, such effects may appear only when the task requires subjects to actively initiate processes to appropriately distribute attention in proportion to the relative subtask demands. In case the task elements clearly provide this environmental support—as in the present experiment in which the magnitude of lateral or longitudinal errors directly specified for experienced drivers what control actions were required—age effects may not occur.

In the study of Schneider and Fisk (1982), subjects were capable of doing the dual task without noticeable deficit when they were encouraged to place all emphasis on the controlled task. Therefore, Schneider and Fisk (1982) considered the tendency of giving priority to automatic subtasks to be a *waste* of resources. However, one should be cautious to draw these kinds of conclusions with regard to tasks such as car driving. In vehicle control, the execution of a automated low-level subtasks, such as course maintenance, is regarded an essential boundary condition for the execution of more controlled higher-level subtasks, such as route planning (Korteling, 1988). Therefore, one

should not advise older subjects to give priority to route planning or maneuvering problems above keeping ones vehicle on the road, just because such strategies lead to a better distributed demand for resources in the laboratory.

The present results suggest that the problems older drivers encounter (e.g., Brainin, 1980; McFarland, Tune, and Welford, 1964; Planek and Fowler, 1971) may not be caused by the *invariant* components of the driving task, which usually are well-learned long before old age. These problems may merely occur in novel situations, such as removal to another city, changing regulations, changing layouts of intersections, or the purchase of a new car, which require subjects to modify elements of long existing psychomotor routines.

The notion that age-deficits may appear when subjects are hampered in their ability to modify previously well-learned psychomotor skills in single- and in dual-task performance, may be considered one aspect of a universal trend in physiological and behavioral development. This trend goes from neuronal plasticity and differentiation, associated with behavioral flexibility and adaptation, to neuronal inertness and stabilization (eventually overshadowed by degeneration), associated with functional specialization and behavioral rigidity. This presumed gradual process of human ontogenesis also signifies that the concept of "old age" and whether or not a skill is developed before or after this life period is equivocal. The present results may thus be regarded to reflect a pervasive, but also indistinct, tendency towards specialization and special-purpose functioning accompanied with decreased psychomotor learning and unlearning capabilities in later adult life.

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General Conclusions

A critical evaluation of literature shows that the major current frameworks for behavioral phenomena in multiple-task performance—that is, (multiple-)resource theory and dual-process theory—are lacking the conceptual depth needed to acquire *accumulating* knowledge. These 'capacity' theories miss explanatory power, are not in harmony with neurobiological evidence and do not sufficiently account for behavioral plasticity with training. The widespread neo-Cartesian conception of attention as 'central supervisory control' does not provide an explanation for what has to be explained, i.e., the process of behavior control itself and thereby performance variations under different dual-task conditions.

In this connection, a cognitive-neuroscience framework for attentional phenomena is introduced, which starts with our present knowledge concerning the basic principles of brain functioning in combination with the nature of attentional limitations in human performance. According to this framework, attentional limitations are determined by the way biological systems satisfy two conflicting requirements: *the need for high associative processing power and flexibility, against the need for coherence and continuity.* This control problem is not solved by a mysterious supervisory attentional system with an *a priory* limited capacity (homunculus). Behavior control originates from the elementary characteristics of neuronal information processing—i.e., coincidence detection, parallel and associative processing and mutual inhibition, cross talk, facilitation, adaptation, and synchronization among connected systems. These underlying mechanisms basically determine capacity limitations as shown in multiple-task performance.

With respect to a behavioral explanation concerning limited capacity in multiple-task situations, both neurobiology and psychological evidence indicate that the nervous system is well-suited for integrated information processing. Attentional limitations generally occur when perceptual, cognitive, or motor operations have to be segregated in task performance. In contrast, the potential efficiency of information processing and action increases with the degree to which dual-task elements are related or coherent, such that subtasks can be performed as a whole. The question whether or not task elements can be integrated or should be kept separate depends on the available control parameters in the combination of subtasks. In general, when there is coherence or compatibility in the processes that have to be combined and difference or incompatibility in processes that should be kept separate, attentional performance will be enhanced. However, when there is difference or incompatibility in the

processes that have to be combined and coherence or compatibility in processes that should be kept separate, mutual inhibition and cross talk will hamper multiple-task performance.

With regard to the mechanisms underlying training effects, skill development can be understood as a gradual transition from information processing by general-purpose brain programs, covering a broad range of task processes, to special-purpose brain programs. Special-purpose brain programs are neuronal networks with a smart computational organization, which means that they are specific and efficient. In comparison to general-purpose programs, special purpose brain programs require lower degrees of activation in order to dominate, i.e., inhibit competing programs. Their execution shows lower metabolic activity, which may be experienced as effortless and subconscious. However, they also require very specific input constellations in order to be activated. Special-purpose programs will usually dominate over general-purpose programs for a given task when both are activated by the same task elements.

Effects of dual-task training are determined by the development of special-purpose brain programs allowing integration or segregation of subtasks. In this connection, the global concept of *similarity* determines the difficulty of coping with specific dual-task requirements. When elementary—often content-dependent—task characteristics are coherent, dependent, or related (*coherent similarity*), individual single-task skills may be associated and integrated into a common special-purpose skill of a higher-order This special-purpose skill capitalizes on the specific peculiarities of the overall task situation. In case of *incoherent similarity*, superficial attributes of subtasks may look similar, but the underlying processing characteristics are different, independent or unrelated. The separation of different processing routines and actions will then become more critical. Consequently, subjects may unintentionally combine the subtasks, such that cross talk or confusion results. Separation of subtasks can partly be accomplished by single-task training, i.e., increasing the specificity of subtask skills. When skills become more special-purpose, the chance that simultaneous actions will depend on the same brain programs will decrease. As opposed to single-task training, however, only in dual-task training, interacting or correlated activity among (to-be--segregated) brain programs can be faced, e.g., capitalizing on control parameters enabling segregation of task elements (*consistent difference*).

In conclusion, dual-task performance and the exclusive value of dual-task training will increase with the degree to which dual tasks entail variables that emerge from the combination of subtasks, i.e., coherent or incoherent similarity or consistent difference.

With reference to the main hypothesis explaining declined multiple-task performance with aging in adulthood, i.e., the *slowing-complexity hypothesis*, several problems were

mentioned. The hypothesis, for example, tends to neglect decreasing neuronal plasticity and decrease of neuronal connections accompanied with hypertrophic changes in neuroglia concerning only selective parts of the brain. For example, relatively great neural losses are found in the prefrontal areas, associated with *behavior adaptation and organization,* and in the hippocampus, associated with the *consolidation of adaptations.*

According to the cognitive neuroscience framework, this selective neuronal decrease may provide a better founded, basis for explanations for aging-related functional decline than the slowing-complexity hypothesis. This may cause several phenomena, such as a reduced potential to utilize general-purpose brain programs (for coping with new situations), to modify or generate new simple-structured special-purpose programs, to deal with emerging variables that affect the integration or segregation of subtasks, to suppress the activation of irrelevant (dominant) routines, to perform tasks requiring self-initiated activity and behavioral adaptations, and finally to process information quickly. The behavioral effects of these problems will increase with task complexity, or the number of required operations.

On the basis of the cognitive-neuroscience framework, the experiments were aimed at the identification of basic mechanisms of age-related problems in multiple-task performance. In the first study, only with regard to the effects of stimulus alternations, confirmation was found for a postulated basic mechanism of general slowing, that is, an aging-related increase in the level of residual neuronal activity. Speed-related differences between the older subjects and the controls were not significant in a familiar driving task (platoon car-following), even when task load was increased, which may partly be related to the high amount of driving experience of the older subjects. Correlations between RT, as determined in laboratory tasks, and RT in car driving as an over-learned practical aggregate of skills, were only found to be high for the brain-damaged subjects. Thus, as opposed to brain-damaged subjects, for older subjects, generalized slowing seemed less general than theoretically should be expected, with regard to car driving as a complex of over-learned skills. Older subjects also appeared particularly slow (slower than the brain-damaged subjects) in RT tasks in which subjects had to respond on combined stimuli. This result suggest that older subjects have difficulties with handling *separate* stimuli that *in combination* specify the correct response. This finding is in line with results of an experiment conducted by Allen and reported by Welford (1958, pp. 193-198) showing that older subjects were unable to combine individual verbal propositions into an overall conclusion, whereas most young subjects had little difficulty in performing the task correctly. From this difficulty with combining information, it is only a small step to experimental manipulation of variables that emerge from the combination of subtasks in a dual task. The manipulation of such *emerging* dual-task variables, while keeping the task equally

complex, was supposed to provide more knowledge concerning the specific problems that older people may have in dual tasks.

The research reported in the next two studies particularly focussed on such variables (i.e., coherent and incoherent similarity). In the second study of this thesis, only the young subjects showed skill integration which was allowed by synchronization of pointer movements (coherent similarity) in a dual-tracking task. Since this kind of coherent similarity typically makes a task more simple, it was concluded that the complexity hypothesis may only hold if subtasks are independent, such that integration cannot play a significant role in task performance. Because all task conditions were dependent on the same visual-spatial-manual 'resources', the results also can not easily be accounted for, by (multiple-) resource conceptions. Following the cognitive-neuroscience approach, it may be supposed that decline of neuronal connectivity make older subjects less able to combine coherent information processes from multiple sources. In other words, the older subjects' ability to integrate sub-skills into a higher-order skill may be poor. This means that only the young subjects performed the dual task more or less like a single task.

The third study, which was based on a dual-tracking task with independently disturbed pointer movements, indicated that the older subjects' performance was especially degraded by two kinds of incoherent similarity, i.e., *superficial similarity* (similar tracking axes) and *incompatibility of similarity* (a mismatch between joystick and display integration). Again, the effects were too specific for a multiple-resource explanation. Because the age effects increased with the degree of incoherent similarity among the independent tracking tasks, the data are in harmony with the previous suggestion that the complexity hypothesis selectively holds for independent subtasks. The paradoxal combination of increased cross talk with incoherent similarity (Chapter 8) and decreased benefit from coherent similarity (Chapter 7) with increasing age, can be explained by assuming that older subjects have a lower number of granular cells. These cells provide the necessary cross-connections for the integration and combination of processing operations, whereas they also determine the number functionally separated channels.

Many of the found results may also be captured as a result of decreasing neuronal plasticity (flexibility) with increasing age. Since plasticity was considered the basic mechanism of learning and adaptation, it is not very surprising that the acquisition of well-trained perceptual-motor skills, such as music playing or car driving, require much more effort as people grow older. According to the cognitive-neuroscience approach, learning may be seen not only as the formation of new, or the coupling of existing, brain programs coding for new processing operations, but also as the modification (or inhibition) of *old* conflicting or inappropriate operations. In this connection, one may question whether age-effects occur in dual-task skills, which were

already well-learned in daily life before old age, and how this is affected by the requirement to modify these components of these skills. This was the main issue addressed in the fourth experiment.

In this final experiment in which experienced drivers performed a vehicle-steering task and a speed-following task in a driving simulator, the older subjects' performance did not differ from younger counterparts, except when the single- or dual task involved routine modification in car following. Hence age-deficits may result from a diminishing ability to modify previously well-learned psychomotor skills in single- and in dual-task performance. This is in support of a presumed age deficit in modifying existing brain programs or in suppressing the activation of irrelevant brain programs. The absence of an effect of the requirement to alternatively prioritize one of the two subtasks was supposed to be compatible with the general idea that age-effects especially appear when the event itself and its accompanying context are ineffective at inducing optimal mental processes, such that there is need for active, internally-generated processes to perform the task. According to the cognitive-neuroscience approach, aging-related degeneration of the brain areas involved in behavior organization and adaptation may hinder such active processes.

On balance, the experimental results have shown that older subjects have difficulty in dealing with the coherent and incoherent relations among subtask elements. This effect may count especially for tasks that were not previously learned. With respect to the absence of age-effects in the over-learned 'normal' car driving tasks (Chapter 6 and 9), it should be noted that this may be caused by the huge driving experience of the older subjects. Furthermore, older subjects seem to be hampered when tasks require skill modification or suppression of over-learned routines. Predictions of the slowing-complexity hypothesis only hold for independent subtasks and/or subtasks that were not previously mastered. Conceptions related to (multiple-) resource theory generally were inadequate to explain the, quite specific, data.

However, the experimental results can be captured on the basis of decreasing neuronal redundancy and flexibility, affecting adaptations of existing brain programs to the peculiarities of new situations and/or situations requiring integration or isolation of brain programs. The age effects found in the unfamiliar task conditions may reflect one aspect of a universal trend in human development. This trend goes from neuronal plasticity and differentiation, associated with behavioral flexibility and adaptation, to neuronal inertness and stabilization (maybe overshadowed by degeneration), associated with functional specialization and decreasing behavioral flexibility. Older subjects generally tend to rely on old over-learned routines and perform all dual tasks as if it were a combination of two different, independent, and unrelated single tasks.

In contrast to existing frameworks, the present cognitive neuroscience perspective provides a frame of reference that is valid in the light of the knowledge that has already been produced by the brain sciences. This framework renders principles for prediction, interpretation and clarification of task performance under various multiple-task conditions. However, it can not (yet) be regarded as a well-defined and completely circumscribed (quantitative) model for predicting age effects in multiple-task situations. For that aim, more quantitative theoretical constructs and sophisticated operational techniques are needed that are capable to bridge the broad gap that still exists between the neurobiological and behavioral domains of explanation.

The results of this study may have various implications for older people in dealing with complex real world tasks. For example, in the area of ergonomics, integration may not always be an optimal solution to cope with the increasing complexity of modern tasks. This may especially count for control and monitoring devices. Therefore controls and displays should not have combined functions, e.g. wiper, light and horn in an automobile should not be mounted on one control handle. Moreover, similarity in design and function of different control and monitoring devices should be avoided. The present development of multi-purpose electronic displays for the presentation of information from different sources may, especially for older people, offer new problems when too much similar information is simultaneously presented at the same location. The results of the final experiment suggest that the problems older drivers encounter may not be caused by the *invariant* components of the driving task, which usually are well-learned long before old age. These problems may merely occur in novel situations, requiring adaptation and flexibility, such as removal to another city, changing regulations, changing layouts of intersections, or the purchase of a new car, which require subjects to modify elements of long existing psychomotor routines.

Summary

In our modern society, complex technological systems typically require people to perform several tasks in a limited period of time. In order to be able to optimize such technological systems, the present thesis aims at explicating some difficulties with regard to the fundamentals of multiple-task performance theory—especially in relation to aging—and at providing some basic theoretical improvements.

First, the fundamental assumptions of the main recent theories concerning multiple-task performance—i.e., resource theories along with the two-modes-of-processing theory—are critically examined. In brief, these theories are based on the notion that human performers possess one or a few 'pools' or supplies of central limited-capacity resources ('fuel metaphor'). On the basis of training, subjects can learn to allocate these limited resources more efficiently to the subtasks—e.g., by optimal allocation strategies or by circumventing the limitations of central attentional resources (automaticity). A theoretical analysis shows that these current frameworks offer rather trivial explanations, lack neurobiological support, and do not sufficiently account for behavioral plasticity with training. The prevalent conception of attention as 'central supervisory control' does not provide an explanation for what has to be explained, i.e., the control process itself. Therefore, the present capacity theories lack the conceptual depth needed to acquire *accumulating* knowledge—that is, knowledge concerning the underlying mechanisms determining performance in complex psycho-motor tasks.

In this connection, a *cognitive neuroscience* framework is invoked, which starts with current knowledge concerning the basic principles of brain functioning in combination with the nature of capacity limitations in human performance. According to this framework, the problem of limited behavioral capacity can not be successfully explained by postulating any *a priory* capacity limitation, but rather by the way biological systems satisfy two conflicting requirements: *massive associative processing power and flexibility against coherent and goal-directed action control*. This control conflict is not solved by a mysterious supervisory attentional system. Behavior control basically emerges from the elementary, self-regulating, characteristics of neuronal information processing, such as coincidence detection or mutual inhibition. Such basic mechanisms also determine capacity limitations as shown in multiple-task perfor-mance.

In addition, neurobiology and psychological evidence indicates that the nervous system is well-suited for integrated information processing. Hence, attentional limitations generally occur when perceptual, cognitive, or motor operations have to be

segregated in task performance, whereas the potential efficiency of information processing and action increases with the degree to which dual-task elements are related or coherent, such that subtasks can be performed as a whole. The question whether or not task elements can be integrated or should be kept separate depends on the available control parameters in the combination of subtasks. In general, when there is coherence or compatibility in the processes that have to be combined and difference or incompatibility in processes that should be kept separate, attentional performance will be enhanced. In contrast, when there is difference or incompatibility in the processes that have to be combined and coherence or compatibility in processes that should be kept separate, mutual inhibition and cross talk will hamper attention performance.

In this connection, the global concept of *similarity* was invoked as an important factor determining the difficulty of coping with specific dual-task requirements. Similarity refers to elementary relationships among subtask with reference to all possible task variables, such as semantic or grammatical similarities, or similarities in color, form, or orientation. Similarity was supposed to facilitate a combined or integrated performance of subtasks and thus to enhance task performance when it involves coherent inputs, processing routines, actions, or subtask goals. This was termed *coherent similarity*. Coherence refers to common, related, corresponding, correlated, or supplementary subtask elements, in relation to the overall objectives of the dual-task. When subtask elements are characterized by coherent similarity, subjects may integrate them into higher-order elements, such that the limitations inherent to the organization of different processes are overcome.

Degrading effects of similarity were supposed to appear when subtask goals, processing routines, timing mechanisms or stimulus-response mapping between subtasks are different or unrelated. This was termed *incoherent similarity*. The selective activation of processing routines and actions will then become more critical. Consequently, subjects may unintentionally combine the subtasks, such that cross talk or confusion results. When tasks are characterized by incoherent similarity, the extent of cross talk interference will depend further on the availability of other control parameters (e.g., elementary visual or phonological cues) enabling segregation of task elements. This was termed *consistent difference*.

With regard to the mechanisms underlying effects of *training*, skill development can be understood as a gradual transition from information processing by general-purpose brain programs, covering a broad range of task processes, to special-purpose brain programs. Special-purpose brain programs are smart neuronal networks with a specific aim and en efficient organization. In comparison to general-purpose programs, special purpose brain programs require lower degrees of activation in order to dominate (inhibit competing programs). Their execution shows lower metabolic

activity, which may be experienced as effortless and subconscious. However, they also require very specific input constellations in order to be activated.

Special-purpose programs will usually dominate over general-purpose programs (mutual inhibition) when both are activated by the same task elements. However, when both refer to different *levels* of the same task or at different *tasks*, special-purpose and general-purpose skills can very well co-exist, e.g. steering a car and route planning in a driving task (different levels) or steering and calculating (different tasks).

By dual-task training, subjects can learn to benefit from coherent similarity or to handle incoherent similarity. With regard to subtasks sharing consistent relationships, individual single-task skills (or brain programs) may be associated and integrated into a common special-purpose skill of a higher-order. This new special-purpose skill capitalizes on the specific peculiarities of the overall task situation. Hence, the dual task will, to a certain degree, be performed as a single-task.

With reference to subtasks characterized by incoherent similarity, training may increase the specificity of skills. When skills become more specific, the chance that simultaneous actions will depend on the same brain programs will decrease. Training may involve separate training of individual task components, or complete dual-task training. Accordingly, both single-task and dual-task training may strengthen the specificity of skills, and thereby enhance dual-task performance. As opposed to single-task training, however, only in dual-task training, interacting or correlated activity among (to-be-segregated) brain programs can be faced, e.g., capitalizing on control parameters enabling segregation of task elements.

The experimental literature reports one major hypothesis explaining why older adults are more penalized than young subjects in multiple-task situations, i.e., the *slowing-complexity hypothesis*. The slowing-complexity hypothesis states that on the basis of cumulative effects of generalized slowing, aging-related performance deteriorations increase with task complexity. Because dual-tasks represent just one of several ways to increase overall task complexity, older adults perform relatively poor in dual tasks.

There are several problems with the slowing-complexity hypothesis. The hypothesis, for example, tends to neglect decrease of neuronal connections accompanied with hypertrophic changes in neuroglia and decreasing plasticity. This decline of neuronal connections does not occur generally, but concerns only selective parts of the brain. For example, large neural losses are found in the prefrontal areas and in the hippo-campus. These areas are particularly associated with *behavior adaptation and organization* and with the *consolidation of adaptations*. These losses reflect a global distinction that can be made between abilities that are relatively sensitive to the effects of aging and abilities that are less sensitive, or 'age-irrelevant'. Age-irrelevant tests generally involve familiar and over-learned skills, such as verbal abilities that do not require

active, internally generated processes, whereas age-sensitive tests involve long-term memory functions (as opposed to immediate memory) and the self-initiated manipulation of unfamiliar materials.

According to the cognitive neuroscience framework, presented in this thesis, aging-related neuronal decline may provide a more appropriate, and from a neurobiological point of view better founded, basis for explanations for aging-related functional problems than the slowing-complexity hypothesis. Decreased neuronal connectivity and plasticity may produce several phenomena, i.e., a reduced potential to utilize general-purpose brain programs (for coping with new situations), to modify or generate new simple-structured special-purpose programs, to deal with emerging variables that affect the integration or segregation of subtasks, to suppress the activation of irrelevant (dominant) routines, to perform tasks requiring self-initiated activity and behavioral adaptations, and finally to process information quickly. The behavioral effects of these problems will increase with task complexity, or the number of required processing operations.

On the basis of the cognitive-neuroscience orientation, it may be supposed that dual tasks require processing operations that are especially difficult for older people. These operations globally can be grasped in terms of the integration and segregation of skills (brain programs), as determined by coherent and incoherent similarity among subtasks. In this context, the experiments described in this thesis were focussed on the identification of problems that older subjects may have with task variables that are specific for dual-tasks and thereby gaining more insight into underlying mechanisms that determine the magnitude of age-effects in (complex) dual-tasks.

Like older people, subjects who have sustained diffuse brain damage usually are also hampered by general psychomotor slowing. In order to explore specific *aging*-related effects of general slowing on information processing, in the *first*, exploratory, study older subjects were compared with brain-damaged subjects in laboratory RT tasks and in more complex car driving RT tasks. The first question concerned possible differences between older-, brain-damaged-, and control subjects in the level of persistent processing activity, which is considered a basic mechanism of generalized slowing. The data showed that only with regard to the effects of stimulus alternations, confirmation was found for the hypothesis that the level of residual neuronal activity increases with age.

Speed-related differences between the older subjects and the controls were not significant in a familiar driving task (platoon-car-following), even when task load was increased. Furthermore, correlations between perception-response speed, as determined in laboratory RT tasks, and perception-response speed in car driving as an over-learned practical aggregate of skills, were only found to be high for the brain-damaged subjects. Thus, as opposed to brain-damaged subjects, for older subjects,

generalized slowing seemed less general than theoretically should be expected, with regard to a complex of over-learned skills, such as car driving.

Finally, older subjects were particularly slow in RT tasks with compound stimuli, which suggested that age effects in dual tasks may be related to problems of older people with task characteristics that emerge from the combination of task elements, such as coherent and incoherent similarity in dual tasks.

The *second study*, described in Chapter 7, investigated age-related differences as affected by coherent similarity, i.e., an emerging dual-task characteristic that was supposed to facilitate task performance. Aging-related differences in a dual task, consisting of two independent single axis compensatory tracking tasks, were expected to increase with *stimulus synchronization*. Stimulus synchronization—a synchronized pattern of disturbance inputs of two moving stimuli—increases subtask coherence and was thus supposed to facilitate skill integration, and thereby integrated dual-task performance. Since stimulus synchronization typically makes a task more simple (in terms of the young subjects' task performance), the complexity hypothesis would predict decreasing age effects. Therefore, the experiment was an explicit test of the complexity hypothesis, which would predict decreasing age effects with stimulus synchronization.

The results showed that the young subjects outperformed the older in dual-task performance only when both subtask stimuli were synchronized. Besides, only the young benefitted from skill integration in order to overcome the negative effects of increased visual competition (interference) between subtasks. It was therefore concluded that the complexity hypothesis may only hold if subtasks are independent, such that skill integration cannot play a significant role in task performance. Because all task conditions were dependent on the same visual-spatial-manual 'resources', the results also could not be accounted for by resource conceptualizations. It was supposed that degradation of neuronal connections make older subjects less able to combine coherent information processes from multiple sources.

The *third study*, presented in Chapter 8, was aimed at age-related performance decrements as affected by incoherent similarity. In a dual task, consisting of two independent single-axis compensatory tracking tasks, two kinds of incoherent similarity were investigated: *incompatibility of integrality*, causing a mismatch of display and joystick integration (similarity) over task levels and *axis similarity* (similarity of tracking axes, i.e., horizontal *vs* vertical). Both task variables were assumed to affect the complexity of stimulus-response mapping, whereas always the same processing modalities were used (visual-spatial-manual).

Tracking error data appeared consistent with the hypothesis that older subjects are extra penalized by incompatibility between control and display integration. Cross-talk

data (correlations between independently disturbed tracking axes) partially confirmed this 'incompatibility of integrality hypothesis'. In general, negative effects of incompatibility of integrality were the greatest when partial integration involved integration of the *response* component. Both performance measures indicated that with increasing axis similarity of subtasks, task performance of the old subjects was more hampered than that of their young counterparts. These data were too specific for a multiple-resource explanation.

As has been stated before, with increasing age, the isolation between active brain mechanisms may decrease. It will then become more difficult to keep simultaneous processing operations separate. This will increase the susceptibility for cross talk in task performance. The paradoxal combination of increased cross talk with incoherent similarity (Chapter 8) and decreased benefit from coherent similarity (Chapter 7) with increasing age, can be explained on the basis of a simple neuronal model, consisting of stable pyramidal and degenerating granular cells.

The magnitude of age effects in single- and dual tasks may be affected by the degree to which performance depends on well-learned skills that were previously developed. In addition, age-effects may be affected by the requirement to modify these skills and by attentional requirements emerging from the mutual relation of subtasks. In the *fourth, final, study*, described in Chapter 9. Effects of skill modification and emerging dual-task processes were examined in an experiment, in which experienced drivers performed a vehicle steering task and a speed-following task in a driving simulator. Car-following was performed under two conditions of familiarity, determining whether or not a normal psychomotor routine had to be modified. In dual-task performance, the demand of subtasks was constant or alternating in counter-phase, which means that the dual-task conditions varied in the requirement to alternatingly prioritize one of the two subtasks. In general, the older subjects' performance did not differ from younger counterparts, except when the single- or dual task involved routine modification in car following. This is in support of a presumed age deficit in modifying existing brain programs or in suppressing the activation of irrelevant brain programs. Introducing demand alternation in counter-phase did not affect dual-task performance and showed no age effects. The finding that counter-phase difficulty alternation did not affect task performance may be explained by the fact that this variation probably was so clearly imposed by the visual input, that subjects automatically responded adequately accordingly. Finally, the data were not completely consistent with the complexity hypothesis.

Samenvatting

In onze moderne samenleving wordt steeds meer gebruik gemaakt van hoogwaardige technologische systemen, waarbij hoge eisen worden gesteld aan het vermogen verschillende taken tegelijkertijd uit te voeren. Voor het kunnen optimaliseren van dergelijke technologische systemen is het daarom goed te beschikken over een breed kennisbestand inzake dubbeltaak-verrichting, gevat in een valide theoretisch kader. Dit is vooral van belang voor de ouderen in onze samenleving die gemiddeld meer moeite hebben met het tegelijk uitvoeren van verschillende taken (dubbeltaken). In dit verband probeert dit proefschrift inzicht te geven in de onderliggende mechanismen die bepalen in welke mate mensen in het algemeen, en ouderen in het bijzonder, moeite hebben met dubbeltaak-verrichting.

De moderne theoretische literatuur gaat ervan uit dat mensen één, of een klein aantal, 'aandacht-reservoir(s)' met een beperkte capaciteit hebben ('capaciteit-theorieën'). Dubbeltaken kunnen goed worden uitgevoerd wanneer deeltaken een beroep doen op verschillende reservoirs ('brandstof-metafoor') of wanneer deeltaken worden geautomatiseerd, zodat ze niet of nauwelijks meer van beperkte aandacht-capaciteit afhankelijk zijn. Impliciet of expliciet wordt daarbij uitgegaan van een centrale aandacht-functie met een beperkte capaciteit die het gedrag superviseert, stuurt en controleert ('homunculus'). Een theoretische analyse laat zien dat capaciteitstheorieën vrij triviale verklaringen voor gedragseffecten opleveren en dat trainingeffecten er moeilijk in kunnen worden verdisconteerd. De conceptie van aandacht brandstof voor centrale sturing en controle van het gedrag levert geen verklaring voor datgene wat verklaard moet worden, nl. dit proces van sturing en controle zèlf. Tot slot zijn de vigerende opvattingen soms moeilijk te verdedigen in het licht van fundamentele kennis over de werking van de hersenen. Kortom, het ontbreekt aan conceptuele diepgang om *accumulerende* kennis te verwerven omtrent de onderliggende mechanismen van prestatie in complexe psychomotorische taken.

Daarom besluit het theoretische deel van dit proefschrift met een zgn. 'cognitive neuroscience' raamwerk gebaseerd op de huidige kennis inzake het functioneren van de hersenen in combinatie met de aard van capaciteitsbeperkingen bij de taakuitvoering. Veel kan verklaard worden op basis van de hoge graad van associatieve interconnectiviteit en parallelle verwerking in het zenuwstelsel, waardoor een onvoorstelbare hoeveelheid informatie flexibel—d.w.z aangepast aan de steeds veranderende omstandigheden—verwerkt kan worden. Daarnaast geldt dat ondanks deze associatieve en parallelle manier van informatieverwerking het zenuwstelsel zodanig functioneert dat het gedrag in principe selectief, coherent en doelgericht is.

In dit verband wordt beargumenteerd dat aandachtsbeperkingen, zoals die in dubbeltaken naar voren komen, bepaald worden door de wijze waarop het zenuwstelsel voldoet aan twee tegenstrijdige eisen: *hoge associatieve verwerkingscapaciteit en flexibiliteit enerzijds en samenhang, organisatie en doelgerichtheid in het gedrag anderzijds*. Dit conflict wordt niet opgelost door een mysterieuze centrale supervisor in het brein, maar is het resultaat van *zelfregulerende* processen in de vorm van een beperkt aantal elementaire neurobiologische mechanismen, zoals bijvoorbeeld reciproke inhibitie (wederzijdse remming).

Uit zowel neurobiologisch als psychologisch onderzoek blijkt dat het zenuwstelsel vooral gericht is op het verwerken van coherente (samenhangende) informatie (*coherente taakovereenkomst*). Als deeltaken samenhang (correlatie, aanvullingen, correspondentie) vertonen, in termen van inputs, verwerkingsoperaties, handelingen of taakdoelen, kunnen ze worden geïntegreerd. Dat betekent dat dubbeltaken als één geheel worden uitgevoerd, waarmee beperkingen die voortvloeien uit de organisatie van deelvaardigheden worden vermeden. Capaciteitsproblemen doen zich primair voor wanneer deeltaken incoherent zijn en (dus) gescheiden moet worden verwerkt. De problemen nemen daarbij toe als deze te scheiden elementen oppervlakkige overeenkomsten vertonen (*incoherente taakovereenkomst*), of wanneer te scheiden elementen onderling weinig consistente verschillen bevatten, waardoor deeltaken makkelijk worden verward.

De onderliggende mechanismen van training-effecten kunnen gezien worden als een geleidelijke overgang van informatieverwerking door *algemene* hersenprogramma's, die flexibel zijn en voor een breed scala van verwerkingsoperaties kunnen worden gebruikt, naar *specifieke* hersenprogramma's. Specifieke hersenprogramma's zijn slimme neuronale netwerken met een beperkt doel en een efficiënte organisatie. In vergelijking met algemene hersenprogramma's vereisen ze minder activatie om andere programma's te kunnen inhiberen. Door hun lagere metabolische activiteit worden ze minder bewust en als moeiteloos ervaren. Om geactiveerd te worden vereisen ze echter ook meer specifieke input. Specifieke programma's domineren gewoonlijk over algemene programma's als beide door dezelfde taak-elementen worden geactiveerd. Echter, als beide betrekking hebben op verschillende *niveaus* van dezelfde taak of op verschillende *taken* kunnen ze goed tegelijk actief zijn, bijvoorbeeld een auto besturen en tegelijkertijd de route plannen (verschillende niveaus) of sturen en hoofdrekenen (verschillende taken). Naarmate, door training, hersenprogramma's meer specifiek worden neemt de kans op interferentie af.

Het bijzondere nut van dubbeltaak-training moet in dit verband worden toegeschreven aan het leren integreren van samenhangende deeltaak elementen of het leren separeren van taken die deze samenhang missen. In dat geval kunnen specifieke hersenprogramma's worden ontwikkeld gericht op het integraal verwerken van

samenhangende (hogere-orde) aspecten van de (dubbel)taak of gespecialiseerd in het separaat verwerken van niet-samenhangende taakelementen, bijvoorbeeld op basis van consistente verschillen tussen de deeltaken.

Voor het verklaren van problemen die ouderen met dubbeltaken hebben is de *general slowing-complexity hypothesis* verreweg het meest geaccepteerd. Volgens deze hypothese nemen prestaties van ouderen af met taakcomplexiteit door een optellende vertraging over alle benodigde stappen in de informatieverwerking. Omdat dubbeltaken complexer zijn dan enkeltaken, en dus meer verwerkingsstappen vereisen, presteren ouderen relatief slecht in dubbeltaken.

Deze verklaring van leeftijdseffecten lijkt op een aantal punten tekort te schieten. Ten eerste wordt geen rekening gehouden met het feit dat de neuronale veranderingen verschillend zijn binnen en tussen verschillende hersengebieden. Daarnaast wordt voorbijgegaan aan het feit dat met het ouder worden het aantal associatieve verbindingen in het zenuwstelsel afneemt, wat gepaard gaat met een afnemende neuronale plasticiteit. Omdat de werking van het zenuwstelsel nu juist gebaseerd is op een hoge associatieve interconnectiviteit, heeft dit wezenlijke gevolgen voor de informatieverwerking. Deze gevolgen zijn vaak eerder oorzaak dan gevolg van trage informatieverwerking. Hierbij kan gedacht worden aan een verminderd potentieel om algemene hersenprogramma's te benutten (in nieuwe situaties) of om snelle specifieke programma's te ontwikkelen. Daarnaast kunnen problemen optreden bij het onderdrukken van irrelevante (dominante) routines, bij het uitvoeren van (ongestructureerde) taken die veel eigen initiatief vereisen, bij het integraal verwerken van samenhangende taakvariabelen en bij het gescheiden houden van niet-samenhangende taakvariabelen (die mogelijk wel op elkaar lijken).

Dit soort onderliggende mechanismen kunnen een goede verklaring opleveren voor de bij ouderen gevonden vertraging in de informatieverwerking, die toeneemt met taakcomplexiteit. In dit verband was het onderzoek gericht op het verwerven van meer inzicht in de taakvariabelen en onderliggende mechanismen die leeftijdseffecten in dubbeltaak-situaties bepalen.

Teneinde meer inzicht te verwerven in *leeftijd*-specifieke vertraging in de informatie-verwerking werden in de eerste studie ouderen vergeleken met jonge mensen met een hersenbeschadiging, die ook een algemene traagheid vertonen. Hierbij bleek o.a. dat correlaties tussen reactiesnelheid in laboratoriumtaken en in rijtaken voor jonge mensen met een hersenbeschadiging hoog waren en laag voor ouderen of een jongere controlegroep. Tevens vertoonden ouderen geen vertraging in de snelheid-gerelateerde maten van een vrij gangbare rijtaak (rem-reactietijd en vertragingstijd), zelfs wanneer de taakbelasting werd verhoogd. Dus, anders dan bij hersenbeschadiging, leek 'general slowing' voor ouderen minder algemeen dan theoretisch mocht worden

verwacht, althans voor een complex van doorgeleerde vaardigheden, zoals autorijden. In deze studie bleek eveneens dat ouderen vooral traag waren (trager dan de hersenpatienten) bij een taak met samengestelde (integreerbare) stimuli, terwijl in de rest van de studie het omgekeerde het geval was. Dit resultaat vroeg om verder onderzoek naar de effecten van dubbeltaken waarin juist dit soort combinatoire effecten van stimuli belangrijk kunnen zijn.

In het tweede experiment werden leeftijdseffecten van stimulus-synchronisatie tussen twee stuurtaken onderzocht. Stimulus synchronisatie impliceerde hier een gesynchroniseerd bewegingspatroon van te besturen stimuli—i.e., coherente taakovereenkomst. Volgens de cognitive neuroscience benadering zal dit de integratie van hersenprogramma's die ten grondslag liggen aan vaardigheden bevorderen, hetgeen bij jongeren mogelijk beter gaat dan bij ouderen. Verwacht werd daarom dat door synchronisatie de leeftijdseffecten zullen worden vergroot. Omdat synchronisatie de stuurtaak eenvoudiger maakt, voorspelt de general slowing-complexity hypothese echter het tegenovergestelde: afnemende leeftijdseffecten.

De resultaten lieten zien dat jongeren in termen van zuivere dubbeltaak-prestaties alleen beter waren dan de ouderen als de deeltaak-stimuli waren gesynchroniseerd. Bovendien bleken alleen jongeren synchronisatie te kunnen gebruiken om negatieve effecten van visuele interferentie te kunnen beperken. Geconcludeerd werd dat de 'slowing-complexity' hypothese bij samenhangende deeltaken geen stand houdt, wat bij veel taken in het dagelijks leven het geval is. Omdat alle taakcondities een beroep deden op visuele, ruimtelijke en manuele 'reservoirs' konden de resultaten evenmin goed worden verklaard met behulp van de vigerende (multiple-)resource(s) theorie. Verondersteld werd dat afname van het aantal neuronale verbindingen ouderen belemmert bij het combineren van samenhangende informatie uit verschillende bronnen

De derde studie was gericht op leeftijdseffecten van overeenkomstige, maar niet samenhangende elementen in twee onafhankelijke compensatoire stuurtaken (incoherente taakovereenkomst). Het betrof hier twee vormen van incoherente taakovereenkomst: incompatibiliteit van integraliteit waarbij taakintegratie verschillend was voor verschillende taakniveaus (joystick-integratie *vs* stimulus-integratie) en (oppervlakkige) overeenkomst m.b.t. de oriëntatie van de stuurassen. Op basis van onafhankelijke variaties van stimulus- en joystick integraliteit werd de taak uitgevoerd onder vier condities van integraliteit-compatibiliteit (volledige integratie of volledige separatie van joysticks en stimuli *vs* integratie van alleen joysticks of alleen stimuli). De conditie met volledige separatie van joysticks en van stimuli werd tevens uitgevoerd met de stuurassen in elkaars verlengde in plaats van loodrecht op elkaar. Verwacht werd dat deze toenemende oppervlakkige gelijkenis van deeltaken de kans op

verwarring groter maakte. Gemeten werden stuurfout en overspraak (correlaties tussen de stuurprestaties in de simultaan uitgevoerde onafhankelijke stuurtaken).

Data betreffende de stuurfout van proefpersonen waren consistent met de hypothese dat ouderen extra gehinderd worden wanneer gedeeltelijke taakintegratie leidt tot een lagere integraliteit compatibiliteit. De overspraak data ondersteunden deze compatibiliteit hypothese alleen in de condities met geïntegreerde joysticks. Beide prestatiematen ondersteunden de hypothese dat de prestatie van ouderen relatief sterk achteruitgaat bij toenemende oppervlakkige overeenkomst van deeltaken. Overeenkomstig experiment 2 kunnen deze specifieke resultaten moeilijk in een resource theorie worden gevat. Verondersteld werd dat, op grond van de leeftijdgerelateerde afname van het aantal neuronale koppelingen, een verklaring eerder gelegen is in verminderde neuronale isolatie van simultaan actieve hersengebieden. De paradoxale combinatie van toenemende overspraak bij incoherente taakovereenkomst (dit experiment) en afnemend profijt van coherente taakovereenkomst (experiment 2) werd aannemelijk gemaakt met een eenvoudig neuronaal model dat bestaat uit stabiele piramidecellen en korrelcellen die met het ouder worden verloren gaan. In dit model leveren de korrelcellen de noodzakelijke 'dwarsverbindingen' voor integratie èn voldoende functioneel gescheiden kanalen voor geïsoleerde verwerkingsoperaties.

De vierde, en laatste, studie was hoofdzakelijk gericht op het kunnen veranderen van een ingeslepen elementaire vaardigheid (routine, specifiek hersenprogramma) in relatie tot leeftijd. Dit werd onderzocht met behulp van een auto-rijtaak waarbij ervaren bestuurders een stuurtaak en een snelheid-volgtaak in een rijsimulator moesten uitvoeren. Het volgen werd uitgevoerd onder twee condities van routine; in de routine-conditie werkte het gaspedaal normaal, terwijl in de routineverandering-conditie de werking van het gaspedaal precies was omgekeerd. De resultaten lieten zien dat ouderen zowel in enkeltaak als in dubbeltaak condities even goed presteerden dan jongeren, behalve wanneer er routineverandering in het spel was. Dit ondersteunt de gedachte dat ouderen moeite hebben met het veranderen van bestaande (specifieke) hersenprogramma's of met het onderdrukken van deze programma's. Dit wordt opgevat als een aspect van een vrij universele trend in de fysiologische en functionele ontwikkeling. Deze trend verloopt van neuronale plasticiteit en differentiatie, geassocieerd met flexibiliteit en aanpassing (bij kinderen) naar neuronale inertie en stabilisatie (glia/neuron verhoging), hetgeen geassocieerd is met functionele specialisatie en een verminderd adaptatievermogen.

Curriculum Vitae

Hans Korteling was born on the 22nd of March 1958, in Apeldoorn. Upon completion of a driver course and Gymnasium-alpha (RSG Goeree-Overflakkee), he studied law for one year at the University of Rotterdam. In august 1978, he commenced his studies in psychology and a few years later in philosophy, both at the University of Amsterdam. His main interests included visual perception, neuropsychology, and philosophy of consciousness. In July 1985, he graduated cum laude for his Master's degree in psychology. From may 1986 until present, he is employed at the TNO Institute for Human Factors as a research psychologist. Since january 1993, he is leader of the Vehicle Control Group of this institute.