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**MULTIPLE-TASK PERFORMANCE:
A CRITICAL REVIEW OF THE LITERA-
TURE AND A COGNITIVE NEURO-
SCIENCE FRAMEWORK**

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Korte samenvatting van:

Multi-task performance: A critical review of the literature and a cognitive neuroscience framework

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MANAGEMENT UITTREKSEL

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 in dit verband goed te beschikken over een breed kennisbestand inzake dubbeltaak-verrichting, gevat in een valide theoretisch kader. Hiermee kunnen voorspellingen worden gedaan over taakbelasting en gedrag in perceptief-motorische en cognitieve dubbeltaken en kunnen (technologische) aanpassingen worden ontwikkeld gericht op vergroting van toegankelijkheid, en participatiegraad voor de "zwakkeren" in onze samenleving, zoals ouderen. In dit verband probeert dit rapport inzicht te geven in de onderliggende mechanismen die bepalen in welke mate mensen moeite hebben met dubbeltaak-verrichting.

De moderne theoretische literatuur gaat ervan uit dat mensen aandacht-reservoir(s) met een beperkte capaciteit hebben. 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. Een theoretische analyse laat zien dat deze "capaciteitstheorieën" vrij triviale verklaringen voor gedragseffecten opleveren en dat training-effecten er moeilijk in kunnen worden verdisconteerd. De conceptie van aandacht als 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 zelf. Tot slot zijn de vigerende opvattingen soms moeilijk te verdedigen in het licht van fundamentele kennis over de werking van de hersenen.

Daarom besluit het rapport met een zgn. "cognitive neuroscience" raamwerk gebaseerd op de huidige kennis inzake het functioneren van de hersenen in combinatie met psychologische kennis omtrent 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 verwerkings-capaciteit en flexibiliteit enerzijds en samenhang, organisatie en doelgerichtheid in het gedrag anderzijds*. Dit conflict wordt niet opgelost door een mysterieuze centrale

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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. Specifieke programma's domineren gewoonlijk over algemene programma's als beide door dezelfde taak-elementen worden geactiveerd. 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.

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Multi-task performance: A critical review of the literature and a cognitive neuroscience framework

J.E. Korteling

EXTENDED SUMMARY

In our modern society, technological developments have altered the nature of jobs and tasks. 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. In order to be able to optimize such technological systems, knowledge with regard to complex-task performance is needed, based on which technical products, processes, and systems involved in daily life can be matched to the capabilities and limitations of people.

Moreover, this kind of knowledge has to be captured into a valid theoretical framework. In this connection, the present report aims at explicating some difficulties with regard to the fundamentals of multiple-task performance theory and to provide some 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 limited-capacity resources ("fuel metaphor"). On the basis of (consistent) 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 neo-Cartesian conception of attention as "central supervisory control" does not provide an explanation for what has to be explained, i.e., the control process itself, and thereby performance variations under different dual-task conditions. Therefore, present theory formation lacks the conceptual depth needed to acquire *accumulating* knowledge—that is, knowledge concerning the underlying mechanisms determining performance in complex psychomotor 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 attentional limitations in human performance. Knowledge concerning the biological 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. Despite this associative way of information processing, behavior normally appears selective, coherent, and goal orientated. It is pointed out that the problem of limited behavioral capacity can not be successfully explained by any *a priori* capacity limitation, but rather by the way *the brain combines its massive associative processing power and flexibility with goal-directed and coherent action control*. This control problem is not solved by a mysterious supervisory attentional system. Behavior control basically emerges 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 basic mechanisms determine capacity variations as shown in dual-task performance. In addition, neurobiology and psychological evidence shows that the nervous system is well-suited for integrated information processing. Attentional limitations generally occur when subtask performance depends on the same processing systems and 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* represents 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 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 have 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 (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. 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, i.e. 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 are 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.

In conclusion, the value of dual-task training will increase with the degree to which dual tasks entail (consistent) variables that enable the combination or segregation of subtasks, i.e., coherent or incoherent similarity or consistent difference. Only when these variables are *consistent* over a period of time, a smart wiring tuned to the invariant properties of the task may develop.

Dubbeltaak-verrichting: een kritisch overzicht van de literatuur en een "cognitive neuroscience" raamwerk

J.E. Korteling

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 in dit verband goed te beschikken over een breed kennisbestand inzake dubbeltaak-verrichting, gevat in een valide theoretisch kader. Hiermee kunnen voorspellingen worden gedaan over taakbelasting en gedrag in perceptief-motorische en cognitieve dubbeltaken en kunnen (technologische) aanpassingen worden ontwikkeld gericht op vergroting van toegankelijkheid, en participatiegraad voor de "zwakkeren" in onze samenleving, zoals ouderen. Ondanks het feit dat er al veel onderzoek is gedaan naar het functioneren van mensen in dubbeltaken, ontbreekt er een goed theoretisch raamwerk.

De moderne theoretische literatuur gaat ervan uit dat mensen één, of een klein aantal, aandachtsreservoirs met een beperkte capaciteit hebben ("capaciteitstheorieën"). Dubbeltaken kunnen goed worden uitgevoerd wanneer deeltaken een beroep doen op verschillende reservoirs of ("brandstof-metafoor") wanneer deeltaken worden geautomatiseerd, zodat ze niet of nauwelijks meer van beperkte aandachtscapaciteit afhankelijk zijn. Impliciet of expliciet wordt daarbij uitgegaan van een centrale aandachtsfunctie 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 training-effecten er onvoldoende in kunnen worden verdisconteerd. De neo-Cartesiaanse conceptie van aandacht als centrale sturing en controle levert geen verklaring voor datgene wat verklaard moet worden, nl. dit proces van sturing en controle zelf. 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.

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Daarom besluit dit rapport 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 onder normale omstandigheden een onvoorstelbare hoeveelheid informatie 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, maar ook flexibel moet kunnen zijn wanneer de (voortdurend veranderende) situatie dat vereist.

Beargumenteed wordt dat aandachtsbeperkingen, zoals die in dubbeltaken naar voren komen, voortkomen uit de wijze waarop het krachtige, flexibele, maar vrij chaotische, principe van associatieve informatieverwerking geregeld wordt, zodanig dat selectief en doelgericht gedrag tot stand komt. Dit gebeurt niet met behulp van 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 coincidentiedetectie, reciproke inhibitie, overspraak, facilitatie en synchronisatie.

Capaciteitsproblemen doen zich primair voor wanneer deeltaken een beroep doen op dezelfde neuronale systemen en wanneer informatie van deeltaken niet samenhangend (coherent) is en (dus) gescheiden moet worden verwerkt. In dat geval worden de problemen nog versterkt wanneer de te scheiden deeltaken oppervlakkige overeenkomsten vertonen waardoor deeltaken makkelijk worden verward (incoherente taakovereenkomst), of wanneer te scheiden informatie weinig consistente verschillen bevat. Het specifieke nut van dubbeltaak-training moet daarom toegeschreven worden aan het leren integreren van vaardigheden op grond van coherente deeltaak overeenkomsten of het leren separeren van deeltaken die deze samenhang missen. In dat geval kunnen op basis van reeds aanwezige general-purpose hersenprogramma's (flexibele specifieke programma's geschikt voor algemene doeleinden) meer domein-specifieke special-purpose hersenprogramma's worden ontwikkeld. Deze zijn 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 die er tussen de deeltaken zullen bestaan.

1 INTRODUCTION

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, that is, 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, which for example elderly or handicapped people are confronted with, have attracted little interest to date. Consequently, 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 can be matched to human capabilities and needs.

Tasks in work situations and in everyday life should be adapted as much as possible to the capabilities and limitations of people. Possible contributions to this could come from human factors analysis of tasks 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 report is focussed on theory development with regard to multiple-task performance and the development of general theoretical principles concerning performance limitations in complex psychomotor tasks. The purpose of the present report 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 the lack of conceptual depth needed to acquire *accumulating* knowledge concerning the *underlying mechanisms* determining performance in complex psychomotor tasks. Therefore the state-of-the-art of multiple-task performance theory will be described and foundations for a theoretical framework, which better incorporates training effects and current knowledge concerning brain functioning, will be developed. The objective of Chapter 2 is to review the main contemporary theories concerning multiple-task performance. In Chapter 3, the fundamental assumptions of these theories will be critically examined. Chapter 4 will be devoted to the formation of a new theoretical framework and Chapter 5 will present and discuss general conclusions.

2 RESOURCE 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 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 frequently 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 variation of 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.

Based on 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 (Fig. 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.

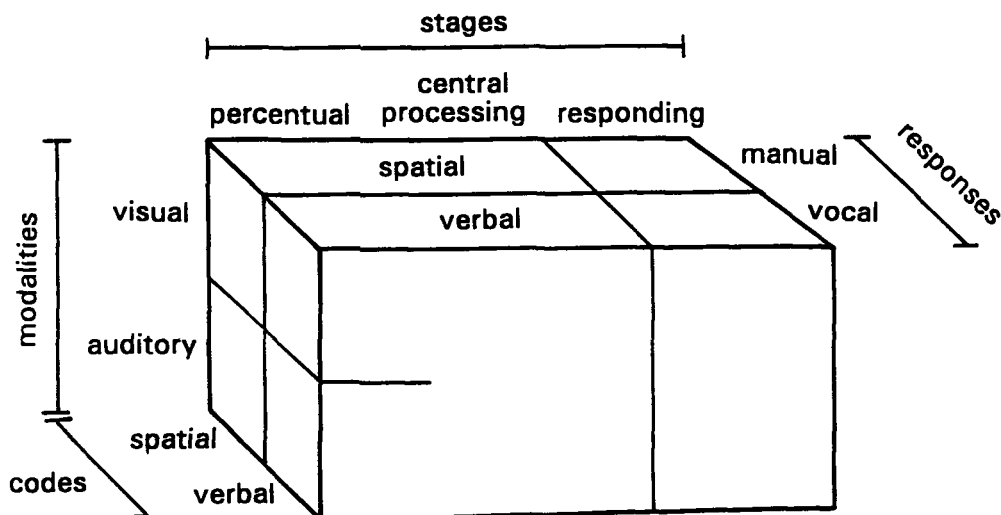


Fig. 1 The structure of multiple-processing resources proposed by Wickens (1984) in R. Parasuraman and R. Davies (Eds), *Varieties of Attention*, New York: Academic Press.

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 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 McLelland, 1992; Neumann, 1984; Logan, 1992).

According to 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-sharingTo 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.

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.

3 A CRITICAL EVALUATION OF RESOURCE THEORIES

3.1 Introduction

The central rapport 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 priori* 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 the fundamentals of capacity theories as explanatory frameworks for human performance in multiple-task situations. These criticisms will deal primarily with the more fundamental assumptions and characteristics of capacity theories. Resource and dual-process theories share the same 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 resources 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 et al., 1992).

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 input² 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 answer the question *why* capacity is limited and what are the variables 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

A 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 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

² 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.

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 problem³. 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 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 interference, is not limited by short-term memory capacity, and does not necessarily give rise to conscious awareness (pre- or postattentive).

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, Servan-Schreiber, and McLelland, 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

³ Since this thesis concerns human-beings, my partiality to potato-sorting machines may sound a bit curious, but it should be considered a major step forwards in comparison to the copper wire of Broadbent (1958) as the metaphorical basis for resource theory.

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 of attention ("postattentive processing").

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.

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 underlie 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. Likewise, Neumann (1984) has argued that automatic processing is not independent of a person's current intentions, i.e., the task situation. Therefore, Logan (1988, 1990) conceives automaticity as *postattentive* rather than *preattentive*. 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 is quite 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 (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.

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 disturbing the performance of that task (e.g., a Stroop task), apparently 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).

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 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 assumption that capacity is fixed. Until very recently, it has thereby provided a spurious reason to divert from the question *why* and *how* capacity should be conceived as fixed and limited in the light of the impressive 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 task performance in different task combinations and training situations.

Unique 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 an excellent review of evidence pointing at a network of distinct anatomical brain areas involved in three kinds of visual-spatial attention: disengagement of 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 the original manuscript) 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, 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 certainly cannot 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 heuristic⁴. 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

⁴ Knowles (1963) for example, analyzed workload of well-trained process operators, for which a fixed-resource conception may be a satisfying first approach.

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 tasks, 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 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. In the next chapter, 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.

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 behavioral 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 Sejnovski, 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 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 do two things at once by *shifting* attention and performance between subtasks. In that case, they actually do not engage in time-sharing, rather they are alternately devoting their full attention to one task and to the other. Such processes also will not be 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).

Although different classifications are possible, two basic types of neurons are often distinguished in the brain: *Golgi type I cells* and *Golgi type II cells*. Golgi I cells (macro neurons) are large, have short, bushy, and tapered dendrites, and a

long, single axons ending in a profusion of terminals. These cells receive information by their dendrites and transmit it over relatively long distances. Golgi II cells (microneurons, granular cells) are smaller. Both their dendrites and axons may receive and transmit information. Their principal role is to integrate information in a nucleus or in a cortical layer.

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 primarily 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 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. These concepts are unbiological abstractions related to the so-called *computer fallacy* (Van de Grind, 1984). 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 Buxitell (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 "neurones"). 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 complex⁵ 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 Beverley, 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.

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,

⁵ 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).

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 subsystems 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 some basic characteristics of this overall 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 perceptuo-motor 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 off 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 a 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 information 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 reasoning. At a specific level of information-organization, we may also select one particular part 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 than 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 facilitation 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? It seems thus 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 phylogenesis), the structure of the nervous system develops such that these 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 try to fly and most birds will not aspire to 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 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 interrupt mechanisms (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).

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. 2). 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 levels, 10 of which cortical, with two *archicortical* nuclei at the top.

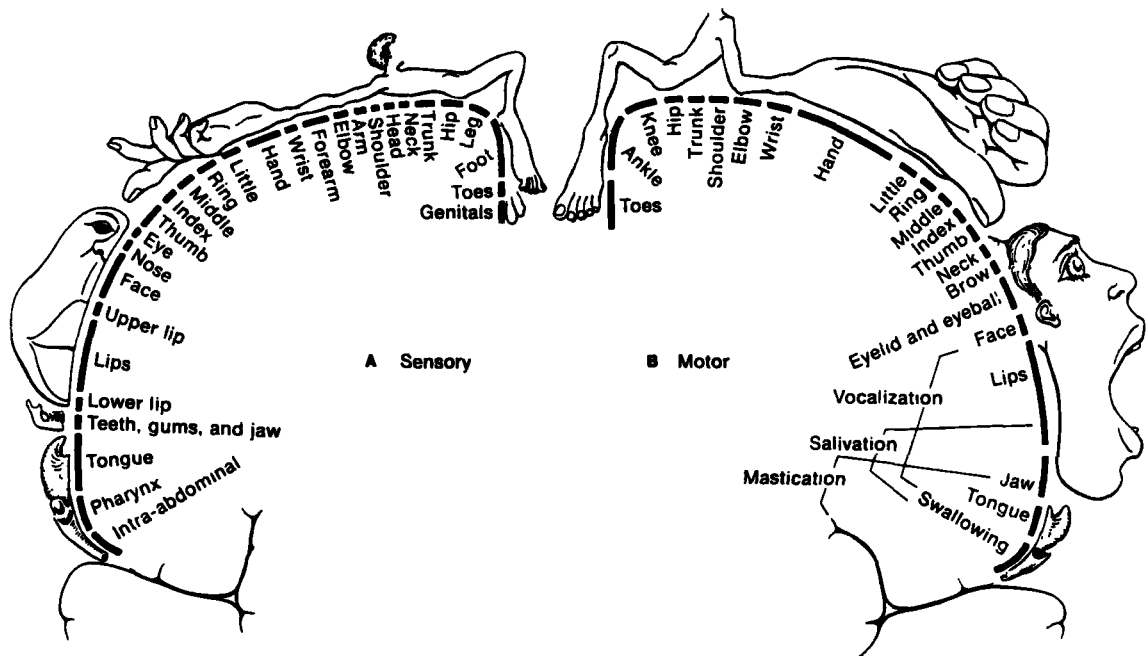


Fig. 2 (A) Map of a transverse section of the somatosensory cortex depicts the point localization of areas corresponding to their peripheral projections—that is, places in the periphery where the stimuli are subjectively "felt". Notice that the region representing the genitalia is tucked discreetly out 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).

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., categorical 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 areas cannot be fingered 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 conceived 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 interdepen-

dency (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), this kind of "decisions" basically emerge from the elementary 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 coherent information rather than to a surplus of coherent 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 emergent 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 Dungelhoff (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 arises not of any *a priori* capacity limitation, but rather from one major computational problem, i.e., *how to combine massive associative processing power and behavioral flexibility with coherent action control*. 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 subtask⁶.

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

⁶ 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.

(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 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 other 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)⁷. 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.

⁷ 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.

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 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-circuitry⁸. 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).

⁸ This process cannot effectively take place in varied mapping tasks.

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 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 programs, 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 argued that dual-task perfor-

mance 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 underlying 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 effectiveness 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 subtasks 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 (or brain programs) cannot be combined or unified to a smaller number of superordinate skills. In the literature, problems concerning multiple-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 effectiveness 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 accidentally 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.⁹ This hierarchical conception of units (skills, tasks, but also stimuli), consisting of elements

⁹ 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.

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. 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 (instructions), available information in relation to the task goals (i.e., affordances, Gibson, 1979), required decisions and actions, feedback loops, and relationships among these processes. Only afterwards, one can reason which underlying processes may determine task performance.

5 GENERAL DISCUSSION AND CONCLUSIONS

Technological developments have altered the nature of jobs and tasks. 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. Research on interfacing new technologies with especially the vulnerable part of the population has attracted little interest to date. 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 can be matched to the capabilities and limitations of people. In this connection, the present report explicates some difficulties with regard to the fundamentals of human performance theory and provides some improvements for this theory. In brief, the issue may be summarized as the lack of conceptual depth needed to acquire *accumulating* knowledge concerning the *underlying mechanisms* determining performance in complex psychomotor tasks.

In order to explain how we perform complex tasks requiring two or more activities in a short period of time and to find the critical factors determining the quality of performance, Chapter 2 presented the main contemporary theories concerning multiple-task performance and Chapter 3, examined the fundamental assumptions of these theories—i.e., resource theories along with the two-modes-of-processing theory. In brief, these theories are based on the notion that human performers possess one or a few "pools" or supplies of limited-capacity resources ("fuel metaphor"). On the basis of (consistent) training, subjects can learn to allocate these limited resources more efficiently to the subtasks, e.g., by optimal

allocation strategies or by circumventing the attentional limitations of a central controller (automaticity). It is argued that the basis of these current frameworks is lacking explanatory power and ontological reality and does not account for behavioral plasticity with training. The prevalent monolithic and neo-Cartesian conception of attention as a "central supervisory controller" does not provide an explanation for what has to be explained, i.e., the control process itself. Therefore, present theory formation lacks the conceptual depth needed to acquire *accumulating* knowledge—that is, knowledge concerning the underlying mechanisms determining performance in complex psychomotor tasks. In general, explanations should link with our knowledge of human behavior as capable of dramatic improvements and with our existing knowledge of the brain as a highly coherent *and* flexible system consisting of an intricate network of functional areas and connecting pathways.

In order to build such a theory, a cognitive neuroscience framework was invoked, which started with current knowledge concerning the basic principles of brain functioning in combination with the nature of attentional limitations in human performance. 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 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 biological 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 possibilities and limitations of attentional capacities, without needing central controllers as an essential "explanatory" construct. The reasoning is briefly summarized below.¹⁰

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 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

¹⁰ The present chapter did not deal with (peripheral) bio-mechanical interference.

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 memory¹¹. 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 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 complica-

¹¹ 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).

tions 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 wiring complexity, content-dependent integration of coherent processes and interference among incoherent processes will be the rule. This means that the problem of limited capacity can not be successfully explained by any *a priori* capacity limitation, but rather by *the way the brain combines massive processing power and behavioral flexibility with goal-directed and coherent action control*. Accordingly, much of what was expressed in the previous chapter is also relevant for selective and focussed attention tasks.

The whole is more than the sum of the individual parts. Therefore, 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 (hue, brightness, saturation), form (square, round, etc.), orientation, movement (speed, direction, flow patterns), size, sound (pitch, loudness, timbre), mapping, timing aspects (rhythm, repetitions, speed), body parts and sense organs, processing operations (arithmetic, mathematic, verbal, spatial, musical, abstraction, etc.). Many of these examples can be further divided in more detailed aspects of similarity. Arithmetic operations, for example, can be divided further into addition, subtraction, 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 (for example on the basis of consistent differences). On the basis of 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 the to-be-combined 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, 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.

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. The following kinds of 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 monolithic attentional controllers? 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 concerning human performance in complex technological settings.

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