Proposal to establish a DFG Priority Program

Human performance under multiple cognitive task requirements: From basic mechanisms to optimized task scheduling

Funding period: 6 years

First funding period: 3 years

Intended beginning: March 2015

Team of applicants:

Speaker:

Apl. Prof. Dr. Andrea Kiesel
Lehrstuhl für Psychologie III
Universität Würzburg
Röntgenring 11
D-97970 Würzburg
Tel.: +49 931 3182766
Email: kiesel@psychologie.uni-wuerzburg.de

First Deputy Speaker:

Prof. Dr. Hermann Müller
Lehrstuhl für Trainingswissenschaft
Justus-Liebig-Universität Gießen
Kugelberg 58
D-35394 Gießen
Tel.: +49 641 9925230
Email: hermann.mueller@sport.uni-giessen.de

Second Deputy Speaker:

Prof. Dr. Iring Koch
Lehrstuhl für Psychologie I
RWTH Aachen University
Jägerstr. 17/19
D-52066 Aachen
Tel.: +49 241 8096012
Email: koch@psych.rwth-aachen.de

Table of Contents

Summary

In modern life, people face many different situations that afford multitasking. Usually such situations are associated with performance decrements, failures, and risks of accidents. Up to now, cognitive psychology and movement science investigated human performance under such multiple cognitive task requirements (i.e. multitasking) mostly independently on each other. The current priority program aims to bring together these largely independent lines of research in order to provide a new integrative theoretical framework to account for this fundamental aspect of human behavior.

Traditional theories in cognitive psychology consider motor actions as a "late" output-related aspect in the chain of information processing steps that can be studied independently from "central" cognitive processes. However, the notion that motor and cognitive processes are functionally independent is challenged because motor processes are crucial for many forms of skill and often represent a particularly challenging part of task performance. Moreover, according to the event-coding framework, cognition and motor control are inextricably linked. Based on this notion, the interdisciplinary combination of cognitive psychology and movement science is well-suited to address questions concerning human multitask performance. However, despite the strong connection of cognition and motor control, cognitive psychology and movement sciences considered the topic "multitasking" from fundamentally different perspectives. While psychology mainly focused on *structural and functional limitations of cognitive processes* when facing multiple cognitive task requirements, movement science emphasized the *plasticity of cognition and the possibility of training*.

Yet, given the societal relevance of human multitasking processes, knowledge on the basic underlying mechanisms is essential for a number of scientific disciplines, and it is therefore important to move this research from disciplinary isolation to an interdisciplinary research field. Without claiming to be complete, multitasking is relevant for scientific disciplines such as ergonomics, computer science, linguistics, cognitive and clinical neuroscience, sports science, and gerontology, in addition to subfields of psychology like work and organizational psychology or developmental psychology. In this priority program, we aim to focus on multiple cognitive task requirements on human performance. Therefore, cognitive psychology and movement science constitute the core disciplines. However, other disciplines that strengthen our understanding of cognitive and performance aspects of multitasking may provide important contributions to the work program.

The combined effort of cognitive psychology and movement science allows the proposed priority program to provide an integrated framework that brings together the issues of structure, flexibility, and plasticity in human multitasking. Specifically, this program aims at generating a scientific matrix that consists of an array of research topics clustered in the following three broad areas. First, it will provide a new, integrative theoretical framework that reconciles the structural perspective of immutable processing bottlenecks with the more flexible cognitive-control perspective. Second, it will re-examine a flexible processing resources metaphor by referring both to the structural perspective in terms of modality-specific capacities and the flexibility perspective in terms of task requirements, motivational, and emotional modulation. Third, it will assess the plasticity of human cognition and motor behavior with respect to action optimization in multiple task situations by focusing on training schedules and the resulting learning processes.

In extension of the flexibility perspective and in the context of an aging society, we also expect that this research will produce a wealth of knowledge with regard to cognitive plasticity that can be used and applied to optimize action in complex task environments which typically involve multiple cognitive requirements. In sum, the present program is aimed at addressing a new research perspective by integrating existing knowledge on a fundamental aspect of human behavior (i.e., "multitasking") across different theoretical perspectives and scientific disciplines. This basic research is expected to have a strong long-term impact on somewhat more applied areas that require high performance in multitasking.

Introduction

In modern life, people often encounter situations in which they plan, perform, or supervise several tasks concurrently, and thus face multiple cognitive task requirements ("multitasking"). Multitasking occurs in many everyday situations. For example, while driving a car, drivers are often engaged in telephone conversations, or while being out for a walk with a friend on a bumpy country lane, the walkers might be engaged in a conversation. Also, working in an office typically requires performing multiple cognitive tasks, such as planning the budget or evaluating the outcome of the company/work group/PhD students, and these tasks might be interrupted by phone calls, incoming emails, or colleagues/clients/students knocking at the door. Multiple task requirements are also prevalent in many other work situations, such as for teachers or surgeons. Most serious examples refer to the chronically over-worked manager who is close to a "burn-out", or to the engineer in an atomic power plant who faces fatal security problems of several systems.

Societal relevance of the topic

As these examples illustrate, the societal relevance of multitasking is beyond controversy. Environments that require multiple cognitive tasks are quite often experienced as demanding, overwhelming, and stressful. Facing such requirements is associated with many societal problems. Risks of accidents demonstrably increase, for example when talking at the telephone while driving (e.g., Strayer & Drews, 2007; Strayer & Johnston, 2001). Further, the increase in mental disorders, like depression or burn-out syndromes, can be at least partially caused by increasing work-related demands (e.g., Baethge & Rigotti, 2010; U. Koch & Broich, 2012; see also, "Stressreport Deutschland 2012"). Consequently, work efficiency is decreased because mental and behavioral disorders are among the three most frequent causes of work incapacities in Germany (Jacoby, Klose, & Wittchen, 2004). And finally, elderly people, whose number is constantly increasing in our aging society, have especially large problems when facing multiple cognitive tasks, such as when walking while being engaged in another task. On average, the risk of falls, with the associated risk of severe injury, increases with age, so that approx. 30% of persons aged 65+ years and approx. 50% of those aged 85+ years fall at least once a year (Beurskens & Bock, 2012a).

It is important to understand the cognitive processes when facing multiple cognitive task requirements in order to increase mental and physical health of the population and to decrease the medical and societal costs that come along with mental disorders and risk of accidents. Thus, increasing our knowledge on basic mechanisms and cognitive control processes when facing multiple cognitive requirements will positively affect our society in many areas. However, while it is important to investigate the causes and consequences of multiple cognitive tasks requirements, like increased risk of accidents (e.g., Simpson, Wadsworth, Moss, & Smith, 2005), increased probability of action errors (e.g., van der Linden, Keijsers, Eling, & van Schaijk, 2005), increased time to respond in each task, we need to go one step further. Multiple cognitive task requirements are simply a societal fact and occur in almost all types of modern work situations as well as in many types of leisure time activities, so that they can hardly be avoided. Thus, we do not just propose to investigate multiple task requirements but also to develop strategies as to how to cope optimally with these requirements. Such strategies might either be related to personal interventions, like training to deal with multiple requirements, or to interventions referring to organization principles, like optimized task scheduling and task combinations.

Multitasking from the cognition-behavior perspective

Please note that the term "multitasking" refers to a very broad range of phenomena. Therefore, it is important to define more specifically (i.e., "operationally") how we understand this term. We speak of multiple task requirements when cognitive processes involved in performing two (or more) tasks overlap in time. Thus, one defining characteristic of multitasking is the existence of time constraints that prevent that each task is operated in temporal isolation. Yet, it is sufficient that cognitive processes, like updating the task rules in working memory, keeping in mind the current status of a task, or evaluating the outcome of a task, occur concurrently in time and are thus simultaneously mentally represented. Consequently, in addition to dual tasks that require concurrent, simultaneous motor responses, also serial task switching as well as task interruptions and resumptions fall within our definition of multitasking. While the current literature does not offer a strict definition of what constitutes a "task" (see Kiesel et al., 2010; Monsell, 2003), we use the term broadly, so that simple stimulus-response translations (e.g., press a response key whenever the letter A appears), continuous tracking tasks, complex mental operations (like multiplying digits), or complex movements (throwing a ball) can constitute a task if a person aims to achieve a discriminable goal state.[1]

In addition to cognitive processing requirements, most tasks entail performing a motor action to achieve the task goal. In the context of multitasking, impairment of performance ("interference"[2]) can occur on several levels (e.g., Koch, 2008; Pashler, 2000, for reviews). Depending on the type of motor activity required by the component tasks, a considerable amount of cognitive activity needs to be devoted to coordination of functionally independent motor actions or requires motor learning to achieve the proper task goals. Yet, classic theoretical approaches assume that in the chain of information processing stages motor action is simply the less interesting "late" output-related stage (e.g., Johnson & Proctor, 2004, for a review) that can be studied independently from "central" cognitive processing stages. However, there are important accounts assuming that motor action and cognition are in fact inextricably linked (e.g., Bratzke, Rolke, & Ulrich, 2009).

For example, the ideomotor hypothesis (e.g., James, 1890) states that motor actions are selected by anticipating the action's sensory consequences, so that the cognitive process of selecting a motor action entails representations in a more "perceptual" format (i.e., referring to anticipated sensory feedback; Greenwald, 1970). This account has been further developed by Prinz (1997) in his common-coding account of perception and action (see also Prinz, Aschersleben, & Koch, 2009) and the generalized "event-coding" framework proposed by Hommel, Müsseler, Aschersleben and Prinz (2001). These accounts suggest abandoning the strict separation of codes (or representations) for perception and action. One important implication of such approaches is that the distinction between perceptual, cognitive (i.e., central), and motor processes is no longer self-evident because both perception and motor behavior are based on "commensurable" common codes (e.g., Butz, Herbort, & Hoffmann, 2007; Hoffmann, 1993). This implication resonates well with recent accounts of human behavior in terms of "embodied cognition". Even though there are diverse and controversial ideas about embodied cognition (e.g., Wilson, 2002, for a review), here we would like to endorse the view that the major function of cognition is to guide action, and that cognition in the context of motor planning is not an abstract, amodal process (as seemingly implied by the notion of "central" processes) but instead includes sensory and motor representational components (e.g., Barsalou, 2008). Hence, assuming an "ideomotor" stance as a moderate version of an embodied cognition view, we argue that cognition and motor control need to be considered in tandem (see also Shin, Proctor & Capaldi, 2010), and this is the reason why we are convinced that the present approach to combine cognitive psychology and movement science is most promising for the investigation of human multitasking.

State of the art and perspectives based on own previous work

Cognitive psychology and movement science both investigated multiple cognitive task requirements. Yet, the research lines are at best partially overlapping and more integration is needed. While research in cognitive psychology has focused on either **structural** limitations or on limitations regarding **flexibility**, movement science has been more interested in **plasticity** and considered training as well as interventions (e.g., with respect to cognitive aging). In the following, we first describe the current state of the art in cognitive psychology and movement science separately. Then we outline our integrated perspective on multiple cognitive task requirements.

[1] Of course, we are aware that this broad definition can lead to inconsistencies, especially for hierarchical tasks or multi-step tasks. Depending on the systemic level of the description, one may consider a sub-goal or a single step as well as the higher-order goal or the complete sequence of steps as a "task".

[2] We use the term "interference" to relate to performance costs due to interfering processes in multitasking. In contrast, the term "crosstalk" is theoretically neutral and refers both to possible performance costs and benefits (see, e.g., Koch & Prinz, 2002).

State of the art in cognitive psychology

Structural perspective. Structural concepts on multiple task performance mainly considered limitations when performing two tasks concurrently. Thereby, limitations were either ascribed to a "bottle-neck" that assumes obligatory (e.g., Pashler, 1998) or highly preferred (Meyer & Kieras, 1997) serial processing at specific processing stages or parallel but strongly resource-limited processing (e.g., Kahnemann, 1973; Norman & Bobrow, 1975). Figure 1 depicts the idea of serial processing stages (e.g., Pashler, 1994, Welford, 1952). Bottlenecks occur in dual-task conditions with strong temporal overlap. Mainly "central" decision processes (i.e., response selection) were identified as bottleneck stage that does not normally operate in parallel (e.g., Janczyk & Kunde, 2010; Jentzsch, Leuthold, & Ulrich, 2007; Kunde, Pfister, & Janczyk, 2012; Pashler, 1994; Paelecke & Kunde, 2007; Schubert, 2008; Welford, 1952). Consequently, if one such process (here response selection for Stimulus 1, S1) occupies the "bot-tleneck" processing stage (indicated by the red shading in Figure 1), the corresponding process for the other task (response selection for S2) has to wait. Thus, bottleneck concepts focus on *structural limitations of central processing stages* while they assume parallel processing for peripheral processing, that is, perceptual and response execution stages (see also Koch, 2008, for a review).

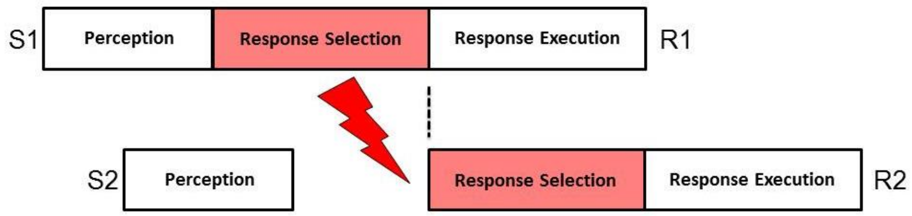

Figure 1. The central bottleneck account implies strictly serial processing at the central stage (adapted from Pashler, 1994). S = Stimulus, R = Response. The arrow indicates interference based on serial processing require-ments at the response selection stage.

Concepts on resource limitations initially assumed unspecific resources that are allocated to different task demands (Kahnemann, 1973; Norman & Bobrow, 1975). Such unspecific concepts were replaced by the assumption of more specific resources, like the assumption of multiple, modality-specific re-sources by Navon and Gopher (1977), or the assumption of multiple resources for stimulus modalities, processing stages, memory codes, and response output as assumed by Wickens (2002; Figure 2 adapted from Wickens & McCarley, 2008). Limitations regarding multiple task requirements occur when-ever the same structural resource is requested by two or more processes (e.g., Manzey, 1993). Thus, all processing stages, not only the central stage, may constitute functional limitations.

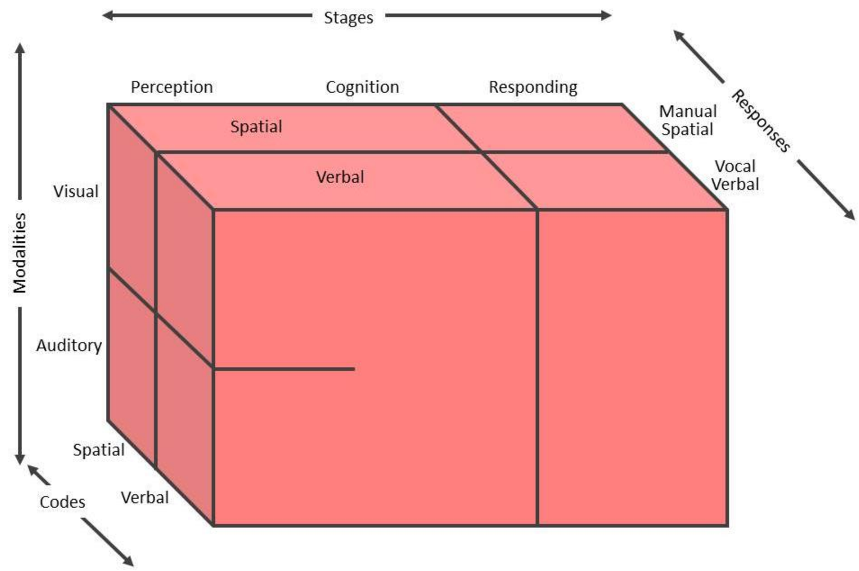

Figure 2. Wickens' concept of multiple, limited resources (adapted from Wickens & McCarley, 2008).

Flexibility perspective. Tombu and Jolicoeur (2003) proposed an account that can be considered as an attempt to integrate the accounts of central (bottleneck) stages and resource-limited but parallel processing (see also Navon & Miller, 2002). They assumed a central bottleneck at which parallel, but resource-limited "central capacity sharing" takes place (see Figure 3). Central resources that are required for response selection are allocated flexibly to processing stages for both tasks. This account can thus explain many recent findings that Task 2 response characteristics impact "backwards" on Task 1 processing (e.g., Fischer, Miller, & Schubert, 2007; Hommel, 1998, Miller, Ulrich, & Rolke, 2009; Schubert, Fischer, & Stelzel, 2008).

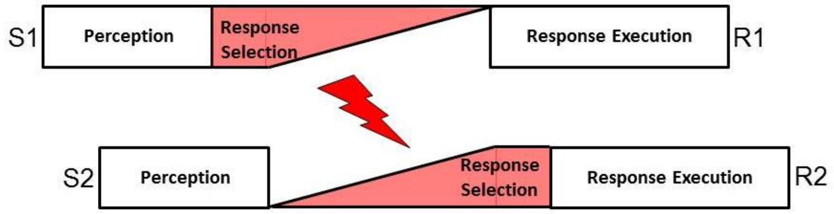

Figure 3. Central capacity sharing account (adapted from Tombu & Jolicoeur, 2003).

Thus, resource concepts entail flexibility regarding how processing resources are allocated to several tasks. In contrast, strict serial processing as assumed by bottleneck accounts can be considered as all-or-none allocation of resources and thus offer no flexibility. However, theorizing on parallel, but resource-limited processing lacks clear explanations of the mechanisms that govern how exactly resources are flexibly allocated. For example, while it is assumed that resources are allocated depending on task priority or expected outcome value (e.g., Wickens, Goh, Helleberg, Horrey, & Talleur, 2003), it remains unclear "who" weights these parameters and which mechanisms implement resource allocation. To address this question, Logan and Gordan (2001) proposed "reconfiguration" as an active control process to allocate resources for the central bottleneck stage. Similarly, Meyer and Kieras (1997) assume adaptive "executive" processes that control response order. However, these active, executive control processes are not well specified (see, e.g., Fischer & Hommel, 2012, for an attempt to characterize different types of control styles) and thus flexibility or limitations of flexibility are currently underspecified concepts within these models.

To address more directly the issue of flexibility when multiple cognitive tasks are required, performance of sequential tasks are preferably considered. It is well established that performance decreases when switching between two (or more) tasks (see Kiesel et al., 2010, or Monsell, 2003, for reviews). These *switch costs* are (at least partly) due to limitations to maintain two task sets at a time in working memory and to flexibly prepare the system for an upcoming task; they are thus due to limited mental task set "reconfiguration". Consequently, responding in task switches takes longer (see Figure 4) because an additional reconfiguration process prolongs task performance. However, other processes have been demonstrated to contribute to task interference and thus to switch costs as well, such as maintenance of working memory content, stimulus valence, response valence, response repetition, item-specific priming, backward inhibition, task expectancy, etc. (see Kiesel et al., 2010, for a review). These other processes are to some degree described in mechanistic terms, whereas a corresponding specification of reconfiguration from the cognitive control perspective is still lacking.

As a further type of multitasking situation, we also consider task interruptions (e.g., Lorch, 1993), that is, settings in which an ongoing task or a task sequence is interrupted by a secondary task. The often observed performance costs of task interruptions and resumptions constitute another example of limitations to flexibly shift attention between tasks (Altmann & Trafton, 2007).

Summary. Theoretical concepts on structural limitations and on limitations regarding flexibility are not sufficiently integrated, and the corresponding research lines are mostly disconnected. Thus, while multiple cognitive task requirements are an important topic in the current societal discourse, and the catchword "multitasking" is often used in the media, psychology clearly lacks an integration of different research lines at the empirical and theoretical level. Research in cognitive psychology accumulated detailed knowledge and specific models, but a "quantum leap" on theorizing is still missing.

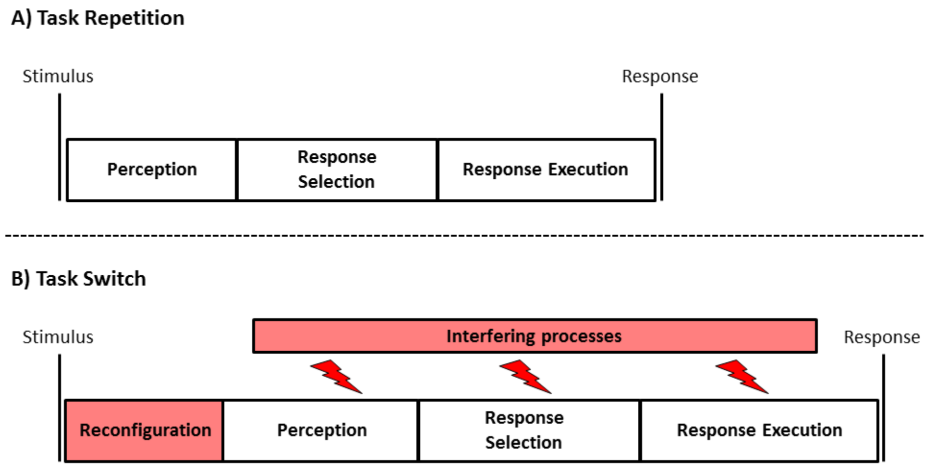

Figure 4. Reconfiguration and other (involuntarily) interfering processes as sources of task-switch costs.

State of the art in movement science

Recent empirical studies in cognitive psychology re-examined both the traditionally assumed functional locus of the bottleneck (see Miller, Ulrich, & Rolke, 2009; Paelecke & Kunde, 2007; or see Koch, 2008, for a review) and the idea of content- and modality-specific interference (e.g., Huestegge & Hazeltine, 2011; Huestegge & Koch, 2013). In addition, training seems to facilitate the ability to conjointly perform two tasks (e.g., Liepelt, Strobach, Frensch, & Schubert, 2011; Schumacher et al., 2001). While especially training studies are a first step to consider plasticity of cognitive processes in human multitasking (e.g., Strobach, Liepelt, Pashler, Frensch, & Schubert, 2013; Strobach, Liepelt, Schubert, & Kiesel, 2012), this aspect is much more prominent in movement science.

Plasticity perspective. In most experimental approaches on multitasking in cognitive psychology, the tasks include a more or less substantial movement component (e.g., pressing or releasing a key), which is considered to be part of the task but is hardly studied separately as potential factor in multitask interference (for exceptions see Bratzke, Rolke, & Ulrich, 2009; Huestegge & Koch, 2013; Philipp & Koch, 2010; Ulrich et al., 2006). Movement science, on the other hand, has dwelled on dual-task or multi-task situations in which at least one of the tasks is a sufficiently challenging motor task, that is, a task where the quality of movement control is crucial for success.

For instance, locomotion is widely studied in these multitask settings. Even though locomotion is highly practiced, it remains a challenging task for the motor control system. Information from different sensory channels (e.g., vision, kinesthetic, vestibular) needs to be processed continuously involving also central processing capacity (Hausdorff, 2005). Especially in elderly persons, walking performance decreases when cognitive secondary tasks, like talking, orienting, or counting, are executed concurrently, increasing the risk of falls (Beurskens & Bock, 2012a). Dual-task costs in locomotion performance are larger when the secondary task is associated with executive or memory functions as compared to simple reaction tasks (Al-Yahya et al., 2011). Interference in cognitive-motor multitasks has thus been explained by limited central processing resources. Alternatively, interference is explained by shared use of more specific resources, like common input modalities (e.g., vision) or common effectors on the output side (e.g., according to the four-dimensional multiple resource model introduced by Wickens, 2008).

As demonstrated by the examples above, movement science has used the same theoretical concepts that are prevalent in cognitive psychology with respect to a structural perspective. The primary difference between these approaches lies in the motoric complexity of the required component tasks, which are often not discrete S-R tasks but ongoing, continuous (or sequential) tasks like locomotion. Nevertheless, *movement science emphasizes the plasticity perspective*, focusing on issues of learning and training in situations that impose multiple cognitive task requirements.

The motor skill learning literature suggests that during extensive practice of motor tasks, information processing is progressively shifted to task-specific encapsulated processing modules at all levels (cf. d'Avella & Pai, 2010; or Hossner, 1995, for an overview). At the input level, information processing is tailored to task-specific solutions where only the relevant information components are processed ("direct parameter specification", cf. Neumann & Klotz, 1994). At the central processing stages, so called "proceduralization" (Anderson & Lebiere, 1998) reduces the involvement of declarative memory (Figure 5). At the output level, less and less conscious control is involved, making the movement robust against diverting processing demands. After extensive practice, movement control can become "automatic" (i.e., it is performed by specific modules without contribution of unspecific central processing units). Automatic movement execution is often described as "non-attentional", that is, as lacking "attentional control". Automatic movements are assumed to be almost completely shielded against any crosstalk from other ongoing activities. In a multitask situation, automatic movements should not show any interference or dual-task costs (conceptualizations of this phenomenon and potential mechanisms are discussed by e.g., Greenwald, 1972; Keele, Ivry, Mayr, Hazeltine, & Heuer, 2003; Lien, McCann, Ruthruff, & Proctor, 2005; for an overview see Müller & Blischke, 2009).

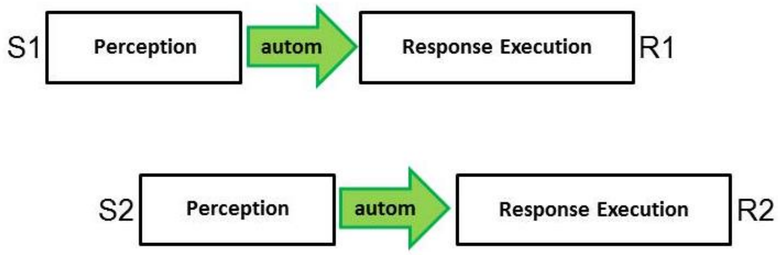

Figure 5. After intensive training, movement control is automatic and does not require limited central capacity.

In that sense, dual tasks have been widely used as a methodological tool and as a window into measuring to which degree a certain movement can be considered as automatic or not. Automaticity has even been operationally defined and quantified by dual-task costs (e.g., Manzey, 1993). It has been demonstrated that dual-task costs can be reduced almost to zero over thousands of practice trials (Blischke, 2001). The degree of automaticity of a movement is a crucial factor affecting the costs in cognitive-motor dual tasks. The rate and the amount of automatization depends on the task characteristics (Wollesen & Voelcker-Rehage, 2013) and shows large inter-individual variation (which can e.g., at least partly be attributed to differences in the dopamine metabolism; Beck, Blischke, & Abler, 2012). Yet, depending on available cognitive resources, similarly automatized movements can reveal different dual-task costs. For example, age-related changes in the available cognitive resources also lead to increased dual-task costs in elderly persons (Krampe, Schaefer, Lindenberger, & Baltes, 2011; Li, Lindenberger, Freund & Baltes, 2001; Lindenberger, Marsiske & Baltes, 2000; Voelcker-Rehage, Stronge, & Alberts, 2006; see also Boisgontier, Beets, Duysens, Nieuwboer, Krampe, & Swinnen, 2013, for a review on postural dual tasks). Note that the cited examples stand for a large number of studies in the field of movement science that can be attributed to the plasticity perspective. They describe how the structure of information processing changes with practice, with age, following neurological impairments etc.

In many applied fields, secondary tasks[3] are used as a diagnostic tool to quantify inter- and intraindividual differences in cognitive resources and automaticity of motor and cognitive tasks. Tests including dual tasks are more sensitive to changes in postural control, leading to a better estimate of the fall risk of a person (Zijlstra, Ufkes, Skelton, Lundin-Olsson, & Zijlstra, 2008). A higher measurement precision also helps to better evaluate balance training interventions to reduce the fall risk or to assess recovery, such as after motor disorders following stroke (Mulder, Zijlstra & Geurts, 2002).

However, dual tasks are not only used to evaluate an intervention, but they are also used as intervention itself. For example, Silsupadol et al. (2009) instructed elderly persons with balance impairments to practice walking in single-task (just walking) or dual-task conditions (walking while concurrently counting backward, naming objects, or spelling words backwards). If tested in single task conditions, both trainings were equally effective, whereas motor and cognitive performance measured under dual-task conditions was improved only after dual-task training. Wollesen and Voelcker-Rehage (2013) explain this

[3] We would like to note that using the term "secondary task" implies a strong priority setting across the component tasks, whereas the term "dual task" is neutral with respect to the priorities that are set by the person, the experimenter, or the situational context.

effect by assuming that dual-task exercise increases the difficulty level, raises the processing load, and by this means boosts performance in the motor and cognitive domain concurrently.

A cognitive secondary task might not only unspecifically raise the work load but also draw attentional control away from the motor task. Interestingly, drawing away attention might even enhance motor learning and motor performance. If the movement is not automatic, this will stimulate the use of the specific processing modules and accelerate the process of automatization. If the movement became automatized, the additional cognitive task prevents the person from allocating unnecessary or even detrimental attention to movement-related motor process. Else, diverting attentional control to an otherwise automatic movement might “de-automatize” control. “Explicit” or “attentional” control could lead to slower and less stable learning compared to so called “implicit motor learning” (Masters, Lo, Maxwell, & Patil, 2008; Steenbergen, van der Kamp, Verneau, Jongbloed-Pereboom & Masters, 2010). There is a large body of literature on skilled performance (e.g., in sport sciences) demonstrating that allocating attention to details of a well learned movement can also degrade performance directly by corrupting a successful automatic control regime (see Wulf, 2013, for an overview).

Summary. In movement science, motor-motor or motor-cognitive task combinations have widely been studied under the perspective of motor learning and automatization. Traditionally, the main focus has been on interference effects as quantification of automaticity, which is used as indicator of intraindividual plasticity and interindividual differences in processing capacities and resource allocation. However, beyond these still significant questions, recent theoretical developments and empirical observations open a new perspective. There seem to be at least some situations where learning a motor task benefits from a cognitive secondary task during training, and cognitive learning might be improved by training under cognitive-motor dual task conditions (see Wollesen & Voelcker-Rehage, 2013, for a review). The mechanisms of this mutual interaction of cognitive and motor tasks are not yet sufficiently understood to predict which task combinations will finally produce positive or negative effects. Future work that tackles this challenge will strongly benefit by a close connection to the current developments in cognitive psychology.

Future research perspectives

According to our view, the interdisciplinary combination of cognitive psychology and movement science is very well-suited to address questions concerning human multitasking performance. However, despite the theoretically postulated inextricable connection of cognition and motor action, cognitive psychology and movement science considered the topic “multitasking” from fundamentally different perspectives. While cognitive psychology either focused on the *structural limitations of cognitive processes* or the *lack of flexibility* when facing multiple cognitive task requirements, movement science considered the *plasticity and the possibility of training*. Naturally, the empirical settings and the types of tasks investigated within the different lines of research differed.

The different perspectives of cognitive psychology and movement science on multiple cognitive task requirements bear a strong potential of cross-fertilization of both fields. Movement science can gain from theorizing about limitations of the cognitive architecture while planning complex movements or actions, and cognitive psychology gains from refining the concept of cognitive plasticity that stimulates training research on how to cope with multiple task requirements.

In addition, knowledge on the basic mechanisms underlying multiple cognitive task requirements is also of theoretical interest for a number of other scientific disciplines. Given the societal relevance of issues concerning multiple cognitive task requirements, it is essential to remove this research from its disciplinary isolation and to frame it in the context of a new interdisciplinary research field. Without claiming to be complete, some examples of other research areas and disciplines are ergonomics, computer science, linguistics, cognitive and clinical neuroscience, sports science, gerontology, in addition to subfields of psychology like work and organizational psychology or developmental psychology. For the proposed priority program, cognitive psychology and movement science represent the core disciplines, even though other disciplines may also contribute to the work program if they help to advance our understanding of cognitive and behavioral aspects of multitasking.

We conjecture that research regarding multiple cognitive task requirements needs two strategies. First, basic research has to deepen our knowledge on underlying mechanisms and principles. And second, an interdisciplinary approach has the potential to consider the topic from different perspectives that will enable us to integrate several lines of research in a common framework. Such an interdisciplinary integration on multiple cognitive task requirements will lead to fundamental insights and gains of knowledge in an emerging interdisciplinary research field that becomes more and more important in modern societies.

Many different factors influence how humans deal with multiple cognitive task requirements. First, the ability to cope with demanding situations increases with practice or training (e.g., Liepelt et al., 2011). Second, differential aspects influence how different persons cope with the same type of multitasking situations. For example, the ability to deal with multiple cognitive requirements decreases with age (Kray & Lindenberger, 2000; Lawo, Philipp, Schuch, & Koch, 2012; Riby, Perfect, & Stollery, 2004), and elderly people seem to develop compensatory strategies to avoid the necessity of multitasking (Baltes & Baltes, 1989). Third, the current affective state as well as the affective appraisal of tasks and multitasking situations might impact on performance (e.g., Dreisbach & Goschke, 2004). In addition, types of tasks and strategies how to manage several action affordances influence multitasking performance (e.g., Oberauer & Kliegl, 2006). And finally, group processes also impact on performance in multitasking settings, especially when several persons have to cooperate on tasks (e.g., Hertel & Scholl, 2006).

Trainings on how to deal with multiple requirements and how to organize different task requirements efficiently are important to construct working environments that do not overburden the individual. On the other hand, however, nobody wants to go back to old-fashioned assembly-line work that requested just single movements of the workers and was related to overstraining of single muscles, monotony, and loss of motivation (Hacker, 2005). Therefore, we need to know which types of multiple task requirements are easy to deal with and probably even related to more efficiency and better evaluations than single task requirements, and which types of trainings are suitable for specific types of multiple cognitive requirements.

Further, such knowledge would not only foster current economics but also shed light on how to deal with multiple cognitive requirements in school and university. This in turn would increase achievements related to all types of educations. In this regard, it is interesting to note first attempts that demonstrate positive aspects of multiple task trainings. Especially concurrent performance of motor and cognitive tasks seem to increase learning in cognitive tasks compared to situations in which pupils train cognitive tasks in isolation (e.g., Zimmer, 2009). Such positive effects of concurrent motor training while engaging in cognitive tasks, are most likely not restricted to young children. Positive effects of combined training might similarly occur in middle aged (e.g., Blischke & Reiter, 2002) as well as elderly (e.g., Voelcker-Rehage & Alberts, 2007).

Moreover, exploring basic mechanisms underlying multiple cognitive task requirements also bears important implications on how engineers construct future technical environments. Most of the environment we deal with each day is man-made. Yet, especially multi-functional technical systems are often not easily operated and not only elderly have immense problems to handle new technology, like computers, smart phones, driver assistance systems, etc. Problems to handle this technology are particularly evident under conditions of time pressure and multiple task requirements. Thus, understanding basic mechanisms helps to advise engineers on how to construe user-friendly human-machine-interactions in time-limited tasks, like in driving situations. Last but not least, it is evident that this research will also inform theories of basic cognitive architecture.

In this proposed program, we aim to focus on multiple cognitive task requirements on performance and behavior. Yet, also subjective consequences, as assessed by self-report or questionnaires, for the person who faces such requirements are clearly relevant. In addition, biological markers, such as stress-related changes in the cortisol level, and neuronal correlates of cognitive processes involved in multitasking, may also help to understand better the mechanisms when dealing with multiple cognitive task requirements.

Previous work of the applicants

The three applicants form a team with both synergistic and complementary expertise and methodological skills. During the last decade, the applicants published extensively on the issue of structure, flexibility, and plasticity of cognition, action control, and motor behavior in both multitasking settings as well as learning and training settings. Specifically, **Andrea Kiesel** and **Iring Koch** contributed to the literature on multitasking together by publishing an extensive review article on task switching (Kiesel et al., 2010, with

191 citations as of October 9, 2013 listed in google scholar). Similar scholarly review articles have been provided by Iring Koch on task inhibition (Koch, Gade, Schuch & Philipp, 2010), on task preparation (Jost, De Baene, Koch & Brass, 2013), and on the mechanisms underlying dual-task performance (Koch, 2008). With respect to the structural perspective, Andrea Kiesel has published well-received empirical contributions on interference in between-task crosstalk in task switching (e.g., Kiesel, Kunde & Hoffmann, 2006; Kiesel, Wendt & Peters, 2007). Iring Koch contributed empirically to the study of crosstalk interference in dual tasks (e.g., Koch & Jolicoeur, 2007; Koch & Prinz, 2002), to inhibition of competing tasks (e.g., Schuch & Koch, 2003) and languages (in bilingual settings; Philipp & Koch, 2009), and to modality-specific constraints in multitasking (e.g., Huestegge & Koch, 2013; Philipp & Koch, 2005). He also edited special issues of international peer-review journals on dual-task performance (Koch & Jolicoeur, 2006) and on task switching (Koch & Brass, 2013). In addition, with respect to flexibility of cognition and action control, Andrea Kiesel has published papers on ideomotor learning (e.g., Pfister, Kiesel & Melcher, 2010), instruction-based control (e.g., Waszak, Pfister, & Kiesel, 2013), conflict control (e.g., Wendt, Kiesel, Geringswald, Purmann, & Fischer, in press), and Iring Koch on both cue-based and predictability-based task preparation processes (e.g., Koch, 2001; Koch & Allport, 2006). Moreover, he has also published in the area of motor sequence learning (e.g., Koch, 2007). This expertise with respect to the issues of structure and flexibility of cognition and motor behavior in various task settings is complemented by the expertise of **Hermann Müller** in the area of flexibility and plasticity of cognition and movement control. Specifically, he published on variability and flexibility of motor skill learning and control of goal-directed action (e.g., Müller, Frank & Sternad, 2007; Pendt, Reuter & Müller, 2011) as well as on the role of cognitive processes in motor learning (Müller, 1997; Müller & Blischke, 2009, for reviews). This expertise in the study of learning processes is important in the present context as it provides the necessary background for the plasticity perspective, focusing on systematic changes of structure as a function of experience and learning.

Together, the combined background of both cognitive psychology and movement science allows the proposed priority program to provide an integrated framework that brings together the three issues of structure, flexibility, and plasticity, which are often discussed in isolation. In this framework, the joint research effort in the context of the proposed priority program is aimed to achieve the following objectives, as outlined in the scientific objectives and work program.

Scientific objectives and Work program

Scientific objectives

The proposed priority program pursues three goals that are constitutive for the work program. The program aims at:

1. providing a new, integrative theoretical framework that reconciles the structural perspective of immutable processing bottlenecks with the more flexible cognitive-control perspective,
2. re-examining a flexible processing “resources” metaphor by referring both to the structural perspective in terms of modality-specific capacities and the flexibility perspective in terms of task requirements, motivational, and emotional modulation,
3. assessing the plasticity of cognition and motor behavior in the context of action optimization in multiple task situations by focusing on training schedules and the resulting learning processes.

Work program

In order to attain the three objectives mentioned above, we aim to generate a scientific matrix that consists of an array of research topics clustered in three broad areas. The individual research projects will typically contribute primarily to one of these clusters, but it is assumed (and desired) that each individual project will also have specific connections to the other clusters, and extending and elaborating these connections will be an important aspect of the work program.

This scientific matrix will be complemented by a governance structure that serves to monitor and evaluate the scientific progress, to ensure the efficiency of education on the PhD and post-doc level, and to strategically anticipate both the topics for the continuation proposal and the needs to ascertain a long-term sustainability of this priority program beyond the DFG funding period.

Our goal is to cluster the individual research projects in *three research areas* (see Table 1). They are ordered along a gradient from pure basic experimental research to research that has the potential to offer insights into more application-oriented questions.

1. Structural perspective: Cognitive bottlenecks, modular resources
2. Flexibility perspective: Cognitive control, action efficiency
3. Plasticity perspective: Cognitive and motor training, learning, life-span development

Table 1
Research matrix based on three project clusters with different (but partially overlapping) perspectives

Dominant Perspective of Research Cluster		
Structure	Flexibility	Plasticity
1. Mechanisms of interference in combining two tasks 2. Mechanisms of interference in switching temporally non-overlapping tasks 3. Structural influence on multi-task performance: Developmental and neuropsychological aspects	1. Basic mechanisms of capacity sharing and parallel processing of independent tasks 2. Cognitive control and intentional set 3. Situative impairment of multitask performance	1. Cognitive learning and training programs I. Influence on cognition 2. Cognitive learning and training programs II. Influence on motor performance and health 3. Expertise and automatisation 4. Organizational measures and interventions to improve multitask performance and reduce associated stress level

Structural perspective: Cognitive bottlenecks, modular resources

Here we subsume research projects that work on research questions using the well-established bottleneck framework or limited-resources concept from a structural (i.e., "deficit-oriented") perspective. This important research area aims to identify the relevant contextual and cognitive variables that lead to impaired performance in multiple task requirements. This includes interindividual differences variables, such as personality, gender, age, and neuropsychological impairment. The aim of studies in this cluster is to identify boundary conditions of multitasking to further refine theories on structural processing limitations and to enrich these theories with the flexibility perspective. Specifically, projects in this cluster will examine performance in quite elementary tasks that enable high experimental control. We identify three partially overlapping sub-areas.

1. Mechanisms of interference in combining two tasks, either simultaneously or in rapid succession: These studies will use variations of the traditional overlapping-task methodology.
2. Mechanisms of interference in switching temporally non-overlapping tasks: These studies use variations of serial switching and task interruption methodology.
3. Structural influence on multitask performance: These studies will focus on developmental (e.g., cognitive aging studies[4]) and neuropsychological aspects (e.g., frontal lobe lesions, beginning dementia; possibly including clinical issues, such as affective disorders).

Flexibility perspective: Cognitive control, action efficiency

This cluster of projects will cover issues of the mechanisms of flexible resource allocation and flexible cognitive control of task set. In contrast to the structural perspective, these projects will examine the boundary conditions for flexible sharing of processes (such as incorporated in capacity sharing models) and flexible shifting of set. The aim of studies in this cluster is to identify boundary conditions of cognitive

[4] In this regard, aging is considered as a quasi-experimental variable, and age-associated differences in structural limitations are investigated. This perspective is complementary to the plasticity perspective, in which it is assessed how these age effects can be compensated by specific training measures.

flexibility to further refine theories on flexible processing and to enrich these theories with the plasticity perspective. We define three sub-areas.

1. Basic mechanisms of capacity sharing and parallel processing of independent tasks: This research is complementary to that in the first cluster and explores the flexibility of the processing system with respect to task demands (e.g., similarity of relevant representations and processes, modality overlap, etc.), instructions, and "operator" needs (strong interaction with projects in the first cluster will be implemented in order to overcome the serial vs. parallel dichotomy).
2. Cognitive control and intentional set: Research in this area focuses on preparatory mechanisms and boundary conditions of flexible (possibly "voluntary") task switching.
3. Situative impairment of multitask performance: Such projects will examine emotional and motivational influences (mostly impairments) of performance; these projects could focus on cognitive-emotional variables (e.g., affective cognitive neuroscience) or on more social-organizational variables that provide a link to the more systemic level of health, work and organizational psychology.

Plasticity perspective: Cognitive and motor training, learning, and life-span development

Projects in this cluster will focus on the active role of subjects to optimize multitask performance in the long term. Relevant variables for this *long-term plasticity* are the temporal organization and requirements of tasks and the issue of whether task-scheduling "strategies" can be effectively employed. The aim of studies in this cluster is to identify the potential of plasticity for multitasking and to combine this perspective with the perspectives of structure and flexibility. This will foster theoretical integration and also serve to enlarge the potential to transfer knowledge on the basic mechanisms regarding multiple cognitive task performance to related disciplines and scientific discourses. We define four sub-areas.

1. Cognitive learning and training programs I. Influence on cognition: These studies focus on the role of specific training regimens in the improvement of cognitive functions. Such studies could focus on basic mechanisms but also on practical, applied benefits in special populations, such as in children, old adults, or neuropsychologically impaired subjects.
2. Cognitive learning and training programs II. Influence on motor performance and health: These studies will use more complex task requirements, such as those requiring fine motor skill or continuous movements. Such studies will focus on action optimization in more applied settings, such as in intervention studies on fall prevention in the elderly.
3. Expertise and automatization: Such projects will explore how acquired cognitive or motor skills change resource requirements (complementary to the structural perspective); here movement science provides a specific focus on motor performance.
4. Organizational measures and interventions to improve multitasking performance and reduce associated stress level: These studies focus on more applied settings and examine the conditions that minimize work load and subjective stress experience in situations that require speeded performance of multiple tasks. Such studies might also have implications for the issue of work-related "burn-out." Even though the general thrust of this priority program is more towards basic research, research from this cluster, and specifically this sub-area, has a strong potential to relate to more applied research programs (e.g., in clinical psychology) outside of the proposed DFG priority program.

Taken together, it is obvious that some projects will be grouped more naturally within a single cluster, whereas other projects could contribute equally to different clusters. In both cases, the projects in these three clusters are supposed to interact strongly. This interaction is needed within each cluster, but it is also required across clusters.

Expected long-term impact of the proposed program

Based on the work in this priority program, research on how people deal with multiple cognitive task requirements, which is a topic of clear societal relevance, will be framed in a broader context in a more interdisciplinary framework, so that knowledge gained in disciplinary isolation will become more fruitful for translation into different disciplines and potential applications. Particularly, we believe that the focus of basic cognitive research on functional and structural processing limitations will be complemented by a strong cognitive-control perspective that emphasizes the flexibility of human cognition.

In extension of the flexibility perspective and in the context of an aging society, we also expect that this research will produce a wealth of new knowledge with regard to cognitive plasticity that can be used and applied to optimize action in complex task environments that are associated with multiple cognitive requirements. This potential with respect to optimization strategies and the efficiency of learning and training schedules will represent the application-oriented aspect of this priority program, even though the major thrust will refer to basic research.

References

Altmann, E. M. & Trafton, J. G. (2007). Timecourse of recovery from task interruption: Data and a model. *Psychonomic Bulletin & Review, 14,* 1079-1084.

Al-Yahya, E., Dawes, H., Smith, L., Dennis, A., Howells, K., & Cockburn, J. (2011). Cognitive motor interference while walking: A systematic review and meta-analysis. *Neuroscience and Biobehavioral Reviews, 35*, 715-728.

Anderson, J., & Lebiere, C. (1998). *The atomic components of thought.* Mahwah: Lawrence Erlbaum.

Baethge, A., & Rigotti, T. (2010). *Arbeitsunterbrechungen und Multitasking.* Dortmund/Berlin/Dresden: BAUA.

Barsalou, L. W. (2008). Grounded cognition. *Annual Review of Psychology, 59,* 617-645.

Baltes, P. B., & Baltes, M. M. (1989). Optimierung durch Selektion und Kompensation: Ein psychologisches Modell erfolgreichen Alterns. *Zeitschrift für Pädagogik, 35*, 85-105.

Beck, F., Blischke, K., & Abler, B. (2012). Dopaminerge Modulation striataler Plastizität–Türöffnerfunktion in der Automatisierung von Willkürbewegungen. *Sportwissenschaft*, *42*, 271–279.

Beurskens, R., & Bock, O. (2012a). Age-related deficits of dual-task walking: A review. *Neural Plasticity*, 131608. DOI: 10.1155/2012/131608.

Beurskens, R., & Bock, O. (2012b). Age-related decline of peripheral visual processing: the role of eye movements. *Experimental Brain Research, 217*, 117-124.

Bialystok, E., Craik, F. I. M., & Luk, G. (2012). Bilingualism: Consequences for mind and brain. *Trends in Cognitive Sciences, 16*, 240-250.

Blischke, K. (2001). Automatisierung einer großmotorischen Kalibrierungsaufgabe durch Prozeduralisierung. *Psychologie und Sport, 8*, 19-38.

Blischke, K., & Reiter, C. (2002). Bewegungsautomatisierung durch Doppeltätigkeits-Üben. *Spectrum der Sportwissenschaften, 14*, 8-29.

Boisgontier, M. P., Beets, I. A. M., Duysens, J., Nieuwboer, A., Krampe, R. T., & Swinnen, S. P. (2013). Age-related differences in attentional costs associated with postural dual tasks: Increased recruitment of generic cognitive resources in older adults. *Neuroscience and Biobehavioral Reviews, 37,* 1824-1837.

Bratzke, D., Rolke, B., & Ulrich, R. (2009). The source of execution-related dual-task interference: Motor bottleneck or response monitoring? *Journal of Experimental Psychology: Human Perception and Performance*, *35*, 1413.

Butz, M. V., Herbort, O., & Hoffmann, J. (2007). Exploiting redundancy for flexible behavior: Unsupervised learning in a modular sensorimotor control architecture. *Psychological Review*, *114*, 1015-1046.

d'Avella, A., & Pai, D. K. (2010). Modularity for sensorimotor control: Evidence and a new prediction. *Journal of Motor Behavior, 42*, 361–369.

Dreisbach, G., & Goschke, T. (2004). How positive affect modulates cognitive control: Reduced perseveration at the cost of increased distractibility. *Journal of Experimental Psychology: Learning, Memory, & Cognition*, *30*, 343-353.

Fischer, R., & Hommel, B. (2012). Deep thinking increases task-set shielding and reduces shifting flexibility in dual-task performance. *Cognition, 123,* 303-307.

Fischer, R., Miller, J., & Schubert, T. (2007). Evidence for parallel semantic memory retrieval in dual-tasks. *Memory & Cognition, 35,* 1685-1695.

Greenwald, A. G. (1970). Sensory feedback mechanisms in performance control: With special reference to the ideomotor mechanism. *Psychological Review, 77*, 73-99.

Greenwald, A. G. (1972). On doing two things at once: Time sharing as a function of ideomotor compatibility. *Journal of Experimental Psychology, 94*, 52-57.

Hacker, W. (2005). *Allgemeine Arbeitspsychologie. Psychische Regulation von Wissens-, Denk- und körperlicher Arbeit.* Bern: Huber.

Hausdorff, J. M., Yogev, G., Springer, S., Simon, E. S., & Giladi, N. (2005). Walking is more like catching than tapping: gait in the elderly as a complex cognitive task. *Experimental Brain Research, 164*, 541-548.

Hertel, G., & Scholl, W. (2006). Grundlagen kooperativer Arbeit. In B. Zimolong & U. Konradt (Hg.), *Ingenieurpsychologie. Enzyklopädie der Psychologie* (Bd. D-III-2, S. 181-216). Göttingen: Hogrefe.

Hoffmann, J. (1993). *Vorhersage und Erkenntnis. Die Funktion von Antizipationen in der menschlichen Verhaltenssteuerung [Prediction and knowledge. The function of anticipation for human action control]*. Göttingen: Hogrefe.

Hommel, B. (1998). Automatic stimulus-response translation in dual-task performance. *Journal of Experimental Psychology: Human Perception and Performance, 24*, 1368-1384.

Hommel, B., Müsseler, J., Aschersleben, G., & Prinz, W. (2001). The theory of event coding (TEC): A framework for perception and action planning. *Behavioral and Brain Sciences, 24*, 849-878.

Hossner, E.J. (1995) *Module der Motorik*. Schorndorf: Hofmann.
Huestegge, L., & Hazeltine, E. (2011). Crossmodal action: Modality matters. *Psychological Research, 75,* 445-451.
Huestegge, L., & Koch, I. (2013). Constraints in task-set control: Modality dominance patterns among effector systems. *Journal of Experimental Psychology: General, 142,* 633-637.
Jacoby, F., Klose, M., & Wittchen, H.-U. (2004). Psychische Störungen in der deutschen Allgemeinbevölkerung: Inanspruchnahme von Gesundheitsleistungen und Ausfalltage. *Bundesgesundheitsblatt, Gesundheitsforschung, Gesundheitsschutz, 47,* 736-744.
James, W. (1890/1981). *The principles of psychology*. Cambridge, MA: Harvard University Press.
Janczyk, M., & Kunde, W. (2010). Does dorsal processing require central capacity? More evidence from the PRP paradigm. *Experimental Brain Research, 203*, 89-100.
Jentzsch I., Leuthold, H., & Ulrich, R. (2007). Decomposing sources of response slowing in the PRP paradigm. *Journal of Experimental Psychology: Human Perception and Performance, 33,* 610-626.
Johnson, D. A., & Proctor, R. W. (2004). *Attention: Theory and practice*. Thousand Oaks, CA: Sage Publications, Inc.
Jost, K., De Baene, W., Koch, I., & Brass, M. (2013). A review of the role of cue processing in task switching. *Zeitschrift für Psychologie, 221*, 5-14. DOI: 10.1027/2151-2604/a000125
Kahneman, D. (1973). *Attention and effort.* Englewood: Prentice-Hall.
Keele, S. W., Ivry, R., Mayr, U., Hazeltine, E., & Heuer, H. (2003). The cognitive and neural architecture of sequence representation. *Psychological Review, 110*, 316–339.
Kiesel, A., Kunde, W., & Hoffmann, J. (2006). Evidence for task-specific resolution of response conflict. *Psychonomic Bulletin and Review*, *13*, 800-806.
Kiesel, A., Steinhauser, M., Wendt, M., Falkenstein, M., Jost, K., Philipp, A. M., & Koch, I. (2010). Control and interference in task switching—A review. *Psychological Bulletin, 136*, 849-874.
Kiesel, A., Wendt, M., & Peters, A. (2007). Task Switching: On the origins of response congruency effects. *Psychological Research*, *71*, 117-125.
Koch, I. (2001). Automatic and intentional activation of task sets. *Journal of Experimental Psychology: Learning, Memory, & Cognition, 27*, 1474-1486.
Koch, I. (2007). Anticipatory response control in motor sequence learning: Evidence from stimulus-response compatibility. *Human Movement Sciences*, *26*, 257-274.
Koch, I. (2008). Mechanismen der Interferenz in Doppelaufgaben [Mechanisms of dual-task interference]. *Psychologische Rundschau*, *59*, 24-32.
Koch, I., & Allport, A. (2006). Cue-based preparation and stimulus-based priming of tasks in task switching. *Memory & Cognition, 34*, 433-444.
Koch, I., & Brass, M. (2013). Task switching—Maturation of a paradigm [Editorial Special Issue "Task Switching"]. *Zeitschrift für Psychologie, 221*, 1-4.
Koch, I., & Jolicoeur, P. (2006). Process-based and code-based interference in dual-task performance [Editorial Special Issue "Process-based and code-based interference in dual-task performance"]. *Psychological Research, 70*, 403-404.
Koch, I., & Jolicoeur, P. (2007). Orthogonal cross-task compatibility: Abstract spatial coding in dual tasks. *Psychonomic Bulletin & Review, 14*, 45-50.
Koch, I., & Prinz, W. (2002). Process interference and code overlap in dual-task performance. *Journal of Experimental Psychology: Human Perception and Performance, 28*, 192-201.
Koch, I., Gade, M., Schuch, S., & Philipp, A. M. (2010). The role of inhibition in task switching – A review. *Psychonomic Bulletin & Review, 17,* 1-14.
Koch, U., & Broich, K. (2012). Das Burn-out-Syndrom. *Bundesgesundheitsblatt, 55*, 161-163.
Krampe, R. T., Schaefer, S., Lindenberger, U., & Baltes, P. B. (2011). Lifespan changes in multi-tasking: Concurrent walking and memory search in children, young, and older adults. *Gait & Posture, 33*, 401-405.
Kray, J., & Lindenberger, U. (2000). Adult age differences in task switching. *Psychology and Aging, 15*, 126-147.
Kunde, W., Pfister, R., & Janczyk, M. (2012). The locus of tool-transformation costs. *Journal of Experimental Psychology: Human Perception and Performance,* 38, 703-714.
Lawo, V., Philipp, A. M., Schuch, S., & Koch, I. (2012). The role of task preparation and task inhibition in age-related task-switching deficits. *Psychology and Aging, 27*, 1130-1137.
Li, K. Z. H., Lindenberger, U., Freund, A. M., & Baltes, P. B. (2001). Walking while memorizing: Age-related differences in compensatory behavior. *Psychological Science, 12*, 230-237.
Lien, M. C., McCann, R. S., Ruthruff, E., & Proctor, R. W. (2005). Dual-task performance with ideo-motor-compatible tasks: Is the central processing bottleneck intact, bypassed, or shifted in locus? *Journal of Experimental Psychology: Human Perception and Performance, 31*, 122-144.
Liepelt, R., Strobach, T., Frensch, P. A., & Schubert, T. (2011). Improved inter-task coordination skills after extensive dual-task practice. *Quarterly Journal of Experimental Psychology, 64*, 1251-1272.

Lindenberger, U., Marsiske, M., & Baltes, P. B. (2000). Memorizing while walking: Increase in dual-task costs from young adulthood to old age. *Psychology and Aging, 15*, 417-436.

Logan, G. D., & Gordon, R. D. (2001). Executive control of visual attention in dual-task situations. *Psychological Review, 108*, 393-434.

Lorch, R. F. (1993). Integration of topic and subordinate information during reading. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 19*, 1071-1081.

Manzey, D. (1993). Doppelaufgabeninterferenz: Neue theoretische und methodische Perspektiven für ein altes Paradigma. In R. Daugs & K. Blischke (Eds.), *Aufmerksamkeit und Automatisierung in der Sportmotorik* (pp. 79–96). Sankt Augustin: Academia.

Masters, R. S. W., Lo, C. Y., Maxwell, J. P., & Patil, N. G. (2008). Implicit motor learning in surgery: Implications for multi-tasking. *Surgery, 143*, 140-145.

Meyer, D. E., & Kieras, D. E. (1997). A computational theory of executive cognitive processes and multiple task performance: Part 2. Accounts of psychological refractory-period phenomena. *Psychological Review, 104*, 749-791.

Miller, J., Ulrich, R., & Rolke, B. (2009). On the optimality of serial and parallel processing in the psychological refractory period paradigm: Effects of the distribution of stimulus onset asynchronies. *Cognitive Psychology, 58*, 273-310.

Monsell, S. (2003). Task switching. *Trends in Cognitive Sciences, 7*, 134-140.

Mulder, T., Zijlstra, W., & Geurts, A. (2002). Assessment of motor recovery and decline. *Gait & Posture, 16*, 198-210.

Müller, H. (1997). Kognition und motorisches Lernen. *Psychologie und Sport, 4*, 74-91.

Müller, H., & Blischke, K. (2009). Motorisches Lernen. In Strauß, B. & Schlicht, W. (Hrsg.), *Enzyklopädie der Psychologie, Themenbereich D, Serie V, Grundlagen der Sportpsychologie* (S. *159-228*). Göttingen: Hogrefe.

Müller, H., Frank, T. D., & Sternad, D. (2007). Variability, covariation, and invariance with respect to coordinate systems in motor control: Reply to Smeets and Louw (2007). *Journal of Experimental Psychology: Human Perception and Performance, 33*, 250-255.

Navon, D., & Gopher, D. (1977). On the economy of the human processing system. *Psychological Review*, *86*, 214-255.

Navon, D., & Miller, J. (2002). Queuing or sharing? A critical evaluation of the single-bottleneck notion. *Cognitive Psychology, 44*, 193-251.

Neumann, O., & Klotz, W. (1994). Motor responses to nonreportable, masked stimuli: Where is the limit of direct parameter specification? In C. Umilta & M. Moscovitch (Eds.), *Attention and Performance XV* (S. 123-150). Cambridge, MA: MIT Press.

Norman, D. A., & Bobrow, D. G. (1975). On data-limited and resource-limited processes. *Cognitive Psychology*, *7*, 44-64.

Oberauer, K., & Kliegl, R. (2006). A formal model of capacity limits in working memory. *Journal of Memory and Language, 55*, 601-626.

Paelecke, M., & Kunde, W. (2007). Action-Effect codes in and before the central bottleneck: Evidence from the PRP paradigm. *Journal of Experimental Psychology: Human Perception and Performance, 33,* 627-644*.*

Pashler, H. (1994). Dual-task interference in simple tasks: Data and theory. *Psychological Bulletin*, *116*, 220-244.

Pashler, H. E. (1998). *The psychology of attention*. Cambridge, MA: MIT Press.

Pashler, H. (2000). Task switching and multitask performance. In S. Monsell & J. Driver (Eds.), *Attention and Performance XVIII* (pp. 277–307)*.* Cambridge, MA: MIT Press.

Pendt, L. K., Reuter, I., & Müller, H. (2011). Motor skill learning, retention, and control deficits in Parkinson's disease. *PLoS ONE* 6(7): e21669. doi:10.1371/journal.pone.0021669.

Philipp, A. M., & Koch, I. (2005). Switching of response modalities. *Quarterly Journal of Experimental Psychology, 58A*, 1325-1338*.*

Philipp, A. M., & Koch, I. (2009). Inhibition in language switching: What is inhibited when switching among languages in naming tasks? *Journal of Experimental Psychology: Learning, Memory & Cognition, 35*, 1187-1195.

Philipp, A. M., & Koch, I. (2010). The integration of task-set components into cognitive task representations. *Psychologica Belgica*, *50*, 383-411.

Pfister, R., Kiesel, A., & Melcher, T. (2010). Adaptive control of ideomotor effect anticipations. *Acta Psychologica, 135*, 316-322.

Prinz, W. (1997). Perception and action planning. *European Journal of Cognitive Psychology, 9*, 129-154.

Prinz, W., Aschersleben, G., & Koch, I. (2009). Cognition and action. In E. Morsella, J. Bargh & P. M. Gollwitzer (Eds.), *The Psychology of Action, Volume 2: Mechanisms of Human Action* (pp. 35-71). Oxford: Oxford University Press.

Riby, L. M., Perfect, T. J., & Stollery, B. T. (2004). The effects of age and task domain on dual task performance: A meta-analysis. *European Journal of Cognitive Psychology, 16,* 863-891.

Schubert, T. (2008). The central attentional limitation and executive control. *Frontiers of Bioscience, 13*, 3569-3580.

Schubert, T., Fischer, R., & Stelzel, C. (2008). Response activation in overlapping tasks and the response selection bottleneck. *Journal of Experimental Psychology: Human Perception and Performance, 34,* 376-397.

Schuch, S., & Koch, I. (2003). The role of response selection for inhibition of task sets in task shifting. *Journal of Experimental Psychology: Human Perception and Performance, 29,* 92-105.

Schumacher, E. H., Seymour, T. L., Glass, J. M., Fencsik, D. E., Lauber, E. J., Kieras, D. E., & Meyer, D. E. (2001). Virtually perfect time sharing in dual-task performance: uncorking the central cognitive bottleneck. *Psychological Science, 12,* 101-108.

Shin, Y. K., Proctor, R. W., & Capaldi, E. J. (2010). A review of contemporary ideomotor theory. *Psychological Bulletin, 136*, 943–974.

Silsupadol, P., Lugade, V., Shumway-Cook, A., van Donkelaar, P., Chou, L., Mayr, U., & Woollacott, M. H. (2009). Training-related changes in dual-task walking performance of elderly persons with balance impairment: A double-blind, randomized controlled trial. *Gait & Posture, 29*, 634-639.

Simpson, S. A., Wadsworth, E. J. K., Moss, S. C., & Smith, A. P. (2005). Minor injuries, cognitive failures and accidents at work: incidence and associated features. *Occupational Medicine, 55*, 99-108.

Steenbergen, B., van der Kamp, J., Verneau, M., Jongbloed-Pereboom, M., & Masters, R. S. W. (2010). Implicit and explicit learning: applications from basic research to sports for individuals with impaired movement dynamics. *Disability and Rehabilitation, 32*, 1509-1516.

Strayer, D. L., & Drews, F. A. (2007) Cell-phone-induced driver distraction. *Current Directions in Psychological Science, 16*, 128-131.

Strayer, D. L., & Johnston, W. A. (2001). Driven to distraction: Dual-task studies of simulated driving and conversing on a cellular phone. *Psychological Science, 12*, 462–466.

Stressreport Deutschland (2012). Report der Bundesanstalt für Arbeitsschutz und Arbeitsmedizin. http://www.baua.de/de/Publikationen/Fachbeitraege/Gd68.pdf?__blob=publicationFile

Strobach, T., Liepelt, R., Pashler, H., Frensch, P.A., & Schubert, T. (2013). Effects of extensive dual-task practice on processing stages in simultaneous choice tasks. *Attention, Perception & Psychophysics, 75*, 900-920.

Strobach, T., Liepelt, R., Schubert, T., & Kiesel, A. (2012). Task switching: effects of practice on switch and mixing costs. *Psychological Research, 76*, 74-83.

Tombu, M., & Jolicoeur, P. (2003). A central capacity sharing model of dual-task performance. *Journal of Experimental Psychology: Human Perception & Performance, 29,* 3–18.

Ulrich, R., Fernández, S. R., Jentzsch, I., Rolke, B., Schröter, H., & Leuthold, H. (2006). Motor limitation in dual-task processing under ballistic movement conditions. *Psychological Science*, *17*, 788-793.

van der Linden, D., Keijsers, G. P. J., Eling, P., & van Schaijk, R. (2005). Work stress and attentional difficulties: an initial study on burnout and cognitive failures. *Work & Stress, 19*, 23-36

Voelcker-Rehage, C., & Alberts, J. L. (2007). Effect of motor practice on dual-task performance in older adults. *Journal of Gerontology: Psychological Sciences, 62B,* P141-P148.

Voelcker-Rehage, C., Stronge, A. J., & Alberts, J. L. (2006). Age-related differences in working memory and force control under dual-task conditions. *Aging, Neuropsychology and Cognition, 13*, 366-384.

Waszak, F., Pfister, R., & Kiesel, A. (2013). Top down vs. bottom-up: When instructions overcome automatic retrieval. *Psychological Research, 77*, 611-617.

Welford, A. T. (1952). The 'psychological refractory period' and the timing of high-speed performance: A review and a theory. *British Journal of Psychology, 43*, 2-19.

Wendt, M., Kiesel, A., Geringswald, F., Purmann, S., & Fischer, R. (in press). Attentional adjustment to conflict strength: Evidence from the effects of manipulating flanker-target SOA on response times and prestimulus pupil size. *Experimental Psychology*.

Wickens, C. D. (2008). Multiple resources and mental workload. *Human Factors, 50*, 449-455.

Wickens, C. D., Goh, J., Helleberg, J., Horrey, W. J., & Talleur, D. A. (2003). Attentional models of multitask pilot performance using advanced display technology. *Human Factors, 45*, 360-380.

Wickens, C. D., & McCarley, J. S. (2008). *Applied attention theory*. Boca Raton: CRC Press.

Wilson, M. (2002). Six views of embodied cognition. *Psychonomic Bulletin and Review*, *9*, 625-636.

Wollesen, B., & Voelcker-Rehage, C. (2013). Training effects on motor-cognitive dual-task performance in older adults. *European Review of Aging and Physical Activity*. DOI: 10.1007/s11556-013-0122-z (online first publication)

Wulf, G. (2013). Attentional focus and motor learning: a review of 15 years. *International Review of Sport and Exercise Psychology, 6*, 77-104.

Zijlstra, A., Ufkes, T., Skelton, D. A., Lundin-Olsson, L., & Zijlstra, W. (2008). Do dual tasks have an added value over single tasks for balance assessment in fall prevention programs? A mini-review. *Gerontology, 54*, 40-49.
Zimmer, R. (2009). *Toben macht schlau! Bewegung statt Verkopfung* (4. Aufl.). Freiburg: Herder.