Andrea Kiesel · Leif Johannsen ·
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Handbook of Human Multitasking

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Introduction: Overview of Concepts and Paradigms

Multitasking is omnipresent in our daily life. We often encounter situations in which we plan, perform, or supervise several tasks concurrently, and thus face multiple cognitive task requirements (“multitasking”). For example, while being out for a walk with a friend on a bumpy country lane, the walkers might be engaged in a conversation. Thus, they face a complex motor task (walking on an uneven surface) simultaneously with a complex cognitive task (communicating with somebody else). Or while driving a car, drivers are occasionally engaged in additional tasks, like, for example, telephone conversations. In this context, we differentiate between a concurrent primary driving task and secondary additional tasks that are performed simultaneously. Also, work environments often require performing multiple tasks, such as engaging in a primary task, like planning the budget or evaluating the outcome of the work group, and these tasks might be interrupted by secondary or intermittent tasks, like phone calls, incoming emails, or colleagues/clients/students knocking at the door.

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 with the risk to fail is associated with many societal problems. Risks of accidents demonstrably increase, for example, when talking at the telephone while driving (e.g., Strayer and Drews 2007; Strayer and 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., Reinecke et al. 2017). Consequently, work efficiency is decreased because mental and behavioral disorders are among the three most frequent causes of work incapacities in Germany (Jacobi et al. 2014, 2016). 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. Multitasking difficulties may exacerbate other aging-related sensorimotor deficits and result in an increased risk of falls in older age. On average, the risk of falls, with the associated risk of severe injury, increases with age, so that approximately 30% of persons aged more than 65 years and approximately 50% of those aged more than

85 years fall at least once a year (Beurskens and Bock 2012). However, multitasking is not only considered a troubling issue. Specifically designed multitasking training programs are also deliberately used to improve performance in single- and multitasks, particularly in the group of elderly persons (Strobach and Karbach 2021).

In line with these rather diverse examples for everyday-types of multitasking, research on multitasking is also diverse. Different research lines apply specific experimental paradigms and concentrate on behavioral performance or on neural representations and processes. Research in more applied areas stresses on the one hand on the performance costs related to multitasking and on the other hand on the benefits of multitasking when considering training effects. This latter research assumes that intensive multitasking training might lead to specific advantages of multitasking abilities that generalize to different types of tasks. Such theoretical reasoning triggered research on specific expert groups. For example, researchers expected that multitasking experts in a specific area, like musician or bilinguals, would show overall increased multitasking performance (yet this evidence appears somewhat controversial when considering meta-analyses and reviews, see, e.g., Wiseheart in this handbook).

Indeed, the different research lines differ even regarding their understanding of the phenomenon "multitasking." Some researchers follow a rather strict definition and speak of multitasking whenever a person performs at least two tasks at the same time (see, e.g., the chapters of Garner and Dux as well as Strayer, Castro and McDonnell in this handbook). In contrast, others use the term "multitasking" more broadly. For example, Koch et al. (2018) suggested to refer to multitasking "when cognitive processes involved in performing two (or more) tasks overlap in time" (p. 558). According to this view, one defining characteristic of multitasking is the existence of time contraints. These time constraints 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, serial task switching as well as task interruptions and resumptions fall within the definition of multitasking.

In the present handbook, we follow such a broader understanding of "multitasking" and include simultaneous as well as sequential multitasking research paradigms. This enables us to cover a wide range of multitasking phenomena. This broader use of the term multitasking seems further justified when considering applied research or everyday multitasking behavior. For example, when driving a car and making a phone call, it remains unclear whether both tasks are actually performed strictly simultaneously (despite that the car of course goes on driving) or whether the driver who engages in driving as primary task switches to the secondary task whenever he/she foresees that the driving task does not require any action in the next seconds.

In addition to different definitions of the phenomenon "multitasking," the literature does not converge regarding the question of what constitutes a "task" (see, e.g., Kiesel et al. 2010; Monsell 2003). Different research areas apply different tasks that involve simple stimulus-response translations (e.g., press a response key whenever the letter A appears), continuous tracking tasks (like steering a car), complex mental operations (like multiplying digits), or complex movements (throwing a ball). Nevertheless, there is agreement to refer to a task if a person aims to achieve a discriminable goal state (e.g., Künzell et al. 2018). Thus, reflex-like behavior (like eye blinking when sensing an air buff) is not considered as task-induced behavior, and in line with this assumption, Janczyk et al. (2014) demonstrated that such reflex-like behavior does not induce dual-task interference. Further, tasks often include several subtasks (see, e.g., the SPIDER model in the chapter by Strayer et al.) and sometimes they are hierarchically structured (e.g., recent theorizing on human-machine interaction suggested to differentiate at least a decision and an action level, see Rothfuß et al. 2020). Thus, tasks might differ in terms of complexity and difficulty, depending on the exact research focus. In addition, also experimental details, like the instructions to the participants, determine the understanding of tasks. In this regard, Dreisbach et al. (2007) demonstrated that the same stimulus-response translation rules might constitute either one task set or two task sets, depending on how participants were instructed. Irrespective of this unclear definition of "tasks" in multitasking contexts, however, there seems to be an implicit agreement of what should be considered as a "task" in the respective research areas because similar types of tasks are actually applied. Thus, to understand the respective underlying mechanisms and processes of multitasking, recipients of the literature should take the actually necessary task requirements into account because interference effects in multitasking often depend on the specific task requirements and the overlap of the task sets.

The aim of this handbook is to provide deeper insights into the different forms of human multitasking from different perspectives. We present and summarize recent research on multitasking from different research fields. The chapters are lined up such that readers can get a broad overview and deeper knowledge on different research lines of multitasking.

First, we consider simultaneous multitasking paradigms from two angles – focusing on discrete dual tasks (Fischer & Janczyk) or on continuous dual task performance (Johannsen, Van Humbeeck, & Krampe). Second, we report research on sequential multitasking studies, focusing on serial task switching (Koch & Kiesel), task interruptions (Hirsch, Koch, & Grundgeiger), and language switching (Philipp & Declerck). Third, we elaborate on the neural basis of multitasking from the dual-task perspective (Garner & Dux) and from the task-switching perspective (Brass & De Baene). Finally, we sketch multitasking in different types of application settings. This includes training of multitasking to improve multitasking performance itself (Karbach & Strobach) and using multitasking training to support performance in other applied domains (Wollesen, Müller, & Voelcker-Rehage), such as the cognitive-motor requirements when driving a vehicle and adding additional secondary tasks (Strayer, Castro & McDonnell). It also includes a view on health issues related to multitasking effects (Li & Downey) as well as the potentially beneficial impact of music expertise on multitasking abilities (Wiseheart). Yet, each chapter can be read as stand-alone contribution and thus readers might choose a different reading order. We therefore hope that this handbook is helpful to gain a deep understanding regarding the complexity of multitasking as an empirical phenomenon and the corresponding basic and applied research, and we hope that you enjoy reading the handbook.

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Part I
Simultaneous Multitasking

Dual-Task Performance with Simple Tasks

Rico Fischer and Markus Janczyk

1 Introduction

The question of whether and how multiple tasks can be performed at the same time has received attention for a long while in psychological research. Early studies on multitasking apparently showed an astonishing ability of performing multiple tasks with only little or no interference (e.g., Allport et al. 1972; Shaffer 1975; Spelke et al. 1976; Wickens 1984). Repeatedly cited examples are studies with skilled typists who were—after only little practice—able to copy-type visually presented words while verbally repeating text messages presented via headphones with only minimal interference (Shaffer 1975). Similarly, piano players shadowed verbal messages and played difficult piano pieces at the same time with performance levels comparable to performing each task alone (Allport et al. 1972; see also Peterson 1969). Such observations of immense human multitasking ability, however, often clash with everyday experiences of severe performance costs when combining rather basic cognitive tasks at the same time. Consequently, one of the most pressing issues in current dual-task research is the characterization of the nature and source of interference when attempting to perform two tasks at once.

An important distinction for this endeavor is that of dual-task performance with *complex* (and often continuous) tasks versus dual-task performance with *simple* tasks. In complex dual-task performance, behavior (e.g., complex mental operations or continuous motor movements) is monitored over a short period of time, and performance is aggregated across the specific time interval (cf. Pashler 1998). While the respective research has advanced theorizing about capacity allocation and has

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accumulated knowledge in more applied contexts (see Chaps. 8, 9, 10, 11 and 12 this volume), it has also been criticized as being only little informative with regard to the underlying cause of dual-task interference. Rather, any observation of minimized dual-task interference may simply be the consequence of temporal task component scheduling instead of true simultaneous processing (cf. Fischer and Plessow 2015; Koch et al. 2018; Meyer and Kieras 1997; Pashler 1998). The study of dual-task performance with simple choice response time RT tasks, in contrast, pursues a rather mechanistic approach in understanding and measuring dual-task interference by highlighting the necessity to study distinct tasks and task component processing. In each of the two simple choice reaction time tasks, a single stimulus is presented that requires a respective response. The stimulus for each task is presented at a discrete moment in time, and the measured RT is unambiguously linked to that stimulus and the respective stimulus-response (S-R) translation process triggered by that stimulus. Therefore, the experimental design is strictly based on discrete trials in which two tasks are performed. This, in principle, enables to avoid the possibility of fast switching between task component processing (see Pashler and Johnston 1998, for a discussion). A critical theoretical assumption underlying the experimental logic in the discrete dual-task approach is that information processing in a task proceeds serially in discrete processing stages, such as perception, response selection, and motor execution (Sternberg 1969). This processing-stage framework allows for a precise examination of dual-task interference at the micro-structure of task component processing (cf. Koch et al. 2018).

The present chapter is dedicated to this basic science perspective on dual-task performance with simple tasks and the identification and explanation of dual-task performance costs. First, we will provide an overview of traditional approaches to studying dual-task performance with simple tasks. Despite the many experimental approaches to assess dual-task performance, we will narrow our chapter to those manipulating the degree of temporal task overlap as a means for creating interference (for other approaches that emphasize sequential dual tasking or comparisons between single- and dual-task performance, see Koch et al. 2018). We will then elaborate on the nature of dual-task costs and discuss the possibility of adaptive dual tasking. Finally, we will sketch out open questions and new developments in research on dual tasking.

2 The Beauty of Mental Chronometry: Psychological Refractory Period Experiments and the (Structural) Reasons of Dual-Task Costs

2.1 The Psychological Refractory Period

In typical experiments to study dual-task performance with simple tasks, two speeded choice RT tasks are performed more or less simultaneously in a single trial. More precisely, two different stimuli (S1 and S2 for Task 1 and Task 2, respectively) are presented at discrete time points with close temporal succession (or simultaneously). However, often the temporal interval between presentation of S1 and S2, the stimulus onset asynchrony (SOA), is systematically manipulated. Participants are usually required to respond in a fixed task order as fast and as accurately as possible with pre-specified responses (R1 and R2 for Task 1 and Task 2, respectively) to S1 and S2. Such experiments show an extremely stable pattern of results: Whereas RTs in Task 1 (RT1) are mostly (though not always) unaffected by the SOA manipulation, RT2 increases dramatically the shorter the SOA, that is, the less the temporal delay between S1 and S2 becomes. Put differently, the more Task 2 temporally overlaps with Task 1 processing, the longer performance in Task 2 takes. These specific performance decrements in Task 2 have been labeled the "psychological refractory period" (PRP) effect, an analogy to the brief temporal inhibition of neural activity following neural spikes (Telford 1931). Critically, however, this analogy insinuates a complete interruption of Task 2 cognitive processing, and its most prominent explanation is based on assumed severe capacity constraints. Consequently, the PRP effect has since been taken as a widely used marker of dual-task costs caused by an assumed capacity-limited processing stage.

2.2 Theoretical Accounts of the PRP Effect

Since the earliest demonstrations of the PRP effect, much research has been dedicated to identify its nature and functional locus. Much of the debates centered around the question whether the bottleneck is of structural or of strategic nature and whether it reflects a single or multiple resource constraints (see Koch et al. 2018, for a comprehensive review). As aforementioned, the PRP effect is extremely robust and occurs in laboratory tasks (for a discussion of exceptions, see Janczyk, Pfister, Wallmeier and Kunde 2014; Lien et al. 2006) as well as in applied driving situations (Bock et al. 2021; Levy et al. 2006) and a number of theoretical propositions aimed at accounting for the dual-task costs as indexed by the PRP effect (Logan and Gordon 2001; Meyer and Kieras 1997; Navon and Miller 2002; Pashler 1994; Tombu and Jolicoeur 2003). For the purposes of the present chapter, we focus on three views that have been invoked most often in multitasking research. For more complex models, we refer the reader, for example, to Salvucci and Taatgen (2008), Byrne and Anderson (2001), or more recent work by Musslick and Cohen (2021).

2.2.1 The Response Selection Bottleneck (RSB) Model

Among those views, the still most prominent model is the *response selection bottleneck* (RSB) model, originally introduced by Welford (Welford 1952; see also Pashler 1994). The observation of the PRP effect despite various non-overlapping stimulus modalities (e.g., auditory S1 and visual S2) and/or response modalities (e.g., vocal R1 and manual R2) renders the suggested locus of capacity constraints

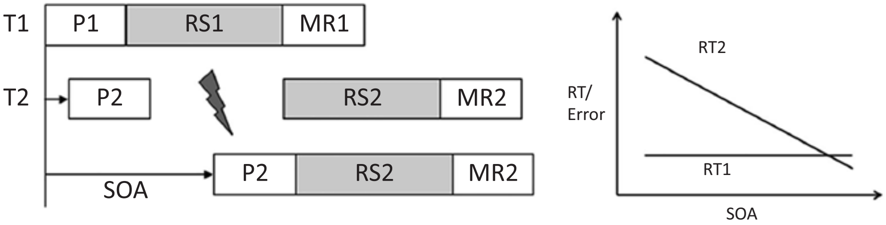

Fig. 1 The response selection bottleneck (RSB) model (Pashler 1994) is visualized in the left panel. Task 1 (T1) and Task 2 (T2) comprise different processing stages that can either proceed in parallel (white stages) or are restricted by capacity limitation s and can proceed only one at a time (gray stages). In conditions of strong temporal overlap of both tasks (short stimulus onset asynchrony, SOA), the critical capacity-limited stage in Task 2 has to wait until the corresponding stage in Task 1 is finished. This idle time of waiting creates the bottleneck at which processing is interrupted and is sometimes termed the "cognitive slack." At long SOAs, however, the critical capacity-limited stages do not overlap, and hence no interruption occurs. An idealized pattern of results is visualized in the right panel (figure is adapted from Fischer and Plessow 2015). *P* perception, *RS* response selection, *MR* motor response

to more "central" stages of cognitive processing, most often to the process of "response selection" (Pashler 1994, 1998).[1] This idea is illustrated in Fig. 1.

Accordingly, processing in peripheral stages (most often related to perception and motor processing) is assumed to be able to proceed in parallel to all other stages without interference. Processing of the central stages, however, underlies *structural* limitations and requires strict serial processing. In other words, bottleneck processing can be directed exclusively to one task at a time. As a consequence, while response selection in Task 1 is ongoing, the corresponding response selection in Task 2 has to wait for completion of bottleneck processing in Task 1. This refractory period assumption is important, as per definition, it precludes any central processing in Task 2 during bottleneck processing in Task 1. Thus, the temporal interruption in Task 2 processing forms the bottleneck ("cognitive slack") in the RSB model (Pashler 1994; Pashler and Johnston 1989). One of the main research questions in explaining the performance costs in discrete dual tasks is whether they originate from a structural limitation in the cognitive architecture, as proposed by the RSB model, or from more strategic task component scheduling.

2.2.2 Capacity Sharing Models

A more flexible group of accounts for dual-task costs are *capacity sharing models*. These models allow parallel processing of central stages; however, they assume a limited resource that has to be shared between tasks and must be allocated to the

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[1] The locus of the capacity limited processing stage has been an important question in the PRP literature, and conceptions of peripheral (e.g., motor locus) or multiple bottlenecks have been put forward (Bratzke et al. 2009; De Jong 1993; Karlin and Kestenbaum 1968; Keele 1973).

tasks in various degrees (Lehle and Hübner 2009; Navon and Miller 2002; Tombu and Jolicoeur 2002, 2003). These models can perfectly account for the PRP effect, and in fact, a bottleneck model as introduced in the previous section represents a special case of an initial 100% to 0% allocation of attentional resources to Task 1 and Task 2, respectively. In contrast to the aforementioned RSB model, however, capacity sharing models allow for immense flexibility as available processing resources can be allocated in various proportions to each task. However, to the degree other ratios are realized and each task is devoted less than 100% of attentional resources, the efficiency of processing both tasks suffers during this period of resource-sharing. Therefore, in contrast to the assumed independence of Task 1 processing of SOA in the RSB model, capacity sharing models are in line with the often observed RT1 increase at short SOA (for a discussion, see Strobach, Schütz and Schubert 2015). It is noteworthy though that these models assume the possibility of true parallel processing of central processing stages (i.e., two central stages running at the same time). A critical aspect of capacity sharing models is that they are surprisingly mute with respect to the assumed nature of the resource(s) that needs to be shared (e.g., Hommel 2020).

2.2.3 Strategic Bottleneck Models and Executive Control Models

Strategic bottleneck models allow people in principle to have flexible control over the scheduling of Task 2 component processing. The executive-process interactive control (EPIC) model of dual-task performance (Meyer and Kieras 1997, 1999), for example, proposes a flexible engagement and disengagement of Task 1 and Task 2 processing between any two processing stages (cf. Schumacher et al. 1999) instead of a rigid central processing limitation as in the RSB model. For example, participants may strategically delay processing of Task 2 components in order to reduce interference between tasks. Some researchers argued that the PRP setup is rather artificial in nature. Especially the extreme focus on Task 1 priority (e.g., fixed task order) and the SOA manipulation may prevent flexible control over task component scheduling and may force participants to strategically adapt to the current experimental requirements producing PRP-typical result patterns (e.g., Meyer and Kieras 1997; Schumacher et al. 1999). The assumption of flexible control over Task 2 processing should in principle allow to eliminate dual-task costs in conditions, which favor the possibility of strategic task scheduling. Accordingly, Schumacher et al. (2001) demonstrated virtually eliminated dual-task costs when participants practiced two tasks with distinct input and output modalities (an auditory-vocal task was combined with a visual-manual task), with no systematic SOA manipulation, and with no instructed task order (Schumacher et al. 2001; but see also Tombu and Jolicoeur 2004). Empirical demonstrations of disappearing dual-task costs are important for at least two reasons. First, previous observations of interference-free dual tasking obtained with continuous dual tasks (Allport et al. 1972; Shaffer 1975; Spelke et al. 1976) can potentially be replicated in conditions using discrete dual tasks, thus avoiding the aforementioned criticism about continuous dual tasks when determining dual-task costs. Second, results suggesting a potential elimination of dual-task costs do not fit well with the assumptions of a structural processing bottleneck as proposed by the RSB model.[2] Although practice-dependent reductions in dual-task costs have since been frequently demonstrated (Halvorson et al. 2013; Hazeltine et al. 2002, 2006; Liepelt, Fischer, Frensch and Schubert 2011; Liepelt, Strobach, Frensch and Schubert 2011; Oberauer and Kliegl 2004; Schumacher et al. 2001; Strobach et al. 2012), an unequivocal interpretation as interference-free dual tasking may be premature (e.g., Ruthruff et al. 2003, 2006; Tombu and Jolicoeur 2004; for a more exhaustive discussion, see Chap. 8).

One of the most prominent theoretical models of cognitive control involvement in dual tasking is the executive control of the theory of visual attention (ECTVA) by Logan and Gordon (2001). ECTVA is a computational model that combines the theory of visual attention (TVA), defining how stimuli are categorized (Bundesen 1990), and the exemplar-based random walk theory (EBRW), a model of response selection (Nosofsky and Palmeri 1997). The processes described in TVA and EBRW are assumed to run twice, that is, separately in each task. Executive control serves to coordinate the subordinate processes. For example, a set of cognitive control parameters (e.g., breath of the attentional focus, task priority, etc.) guarantees the correct engagement/disengagement of task component processing (task-set shifting). The task priority parameter π enables the strong processing prioritization of Task 1 stimuli in typical PRP experiments. The feature catch parameter c realizes the perceptual organization of displayed visual information leading to a widened or narrowed attentional scope. These control parameters are usually set by instructions and enable that stimuli of each task are correctly mapped onto the respective responses in each task to avoid the risk of response reversals/confusion (dual-task binding problem). The advantage of ECTVA is that it clearly spells out how dual-task interference arises and by which mechanisms it can be reduced.

2.3 The PRP Effect Beyond Stimulus-Response Translations

The mainstream of research on the PRP effect has focused on dual-task performance with two simple choice RT tasks. It is important to note, however, that the PRP effect is a rather broad phenomenon and by no means restricted to a combination of two speeded simple tasks with two response selection processes. Research with so-called *hybrid* experiments demonstrated, for example, that access to and retrieval from short-term memory (STM) create bottlenecks that interfere with

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[2] Note that the proposal of latent bottlenecks as a consequence of extensive practice (Ruthruff et al. 2003) is in line with the RSB model to explain dual-task cost reductions. Similarly, optimized attention allocation between tasks, automatization, and increased information processing speed, as well as improved executive control skills, have been proposed to account for dual-task cost reduction after practice and are also well in line with capacity sharing and control models of dual-task performance (for a recent review, see Strobach and Schubert 2017).

concurrent cognitive processing. In such hybrid experiments, a classical speeded choice RT task is paired with an STM task (see Jolicoeur et al. 2002 for a review). In their seminal study, Jolicoeur and Dell'Acqua (1998) asked participants to encode and maintain briefly presented stimuli for later report in Task 1 and to respond to auditory stimuli in Task 2. Although no response selection was required for Task 1, manual responses in Task 2 were delayed at short SOA indicating a PRP effect. These and similar findings show that memory processes (e.g., STM consolidation and selection of items in memory) interfere with simultaneous response selection processes (see also Janczyk 2017; Janczyk and Berryhill 2014; Koch and Jolicoeur 2007; Koch and Prinz 2002). Likewise, a choice RT task interfered with a concurrent STM task as Task 2, resulting in worse STM performance at high temporal overlap between both tasks (Jolicoeur 1999).

A further example is the *attentional blink* in which two STM tasks are paired in rapid sequence (Raymond et al. 1992). Two target items (T1 and T2) have to be detected in a rapid visual stream presentation (RVSP). At a specific short temporal interval, the speeded encoding of T1 dramatically reduces the detection of the subsequent T2. T2 detection is unimpaired though when the temporal interval between T1 and T2 is sufficiently long or when T1 can be ignored. Despite the lack of any motor component, the attentional blink bears strong similarities to the PRP effect (e.g., Garner et al. 2014), as both sensory consolidation (attentional blink) and attentional limitations in response selection (PRP) create cognitive processing bottlenecks (Marti et al. 2012; Tombu et al. 2011).

Therefore, it seems important to examine the nature of various cognitive bottlenecks that arise irrespective of response selection processes as they offer insights in the processing constraints that may suggest strategies of performance optimization. For example, despite the similarities between PRP and attentional blink, the strategies of performance optimization differ in both paradigms. While increased proactive control leads to improved performance in PRP experiments, performance in the attentional blink benefits from reduced investment of cognitive control (Olivers and Nieuwenhuis 2006).

3 The Usability of the Processing-Stage Framework for Hypothesis Testing

The discrete processing-stage framework underlying the PRP approach has inspired many researchers to develop experimental strategies and designs to put important implications of the RSB model to test and to localize the origin of experimental effects within the stream of task processing. Particularly useful appears a combination of what is known as the *locus of slack* logic and the *effect propagation* logic, which are illustrated in Figs. 2 and 3, respectively. Their strength is the possibility to determine the locus of specific cognitive processes in reference to the assumed processing bottleneck.

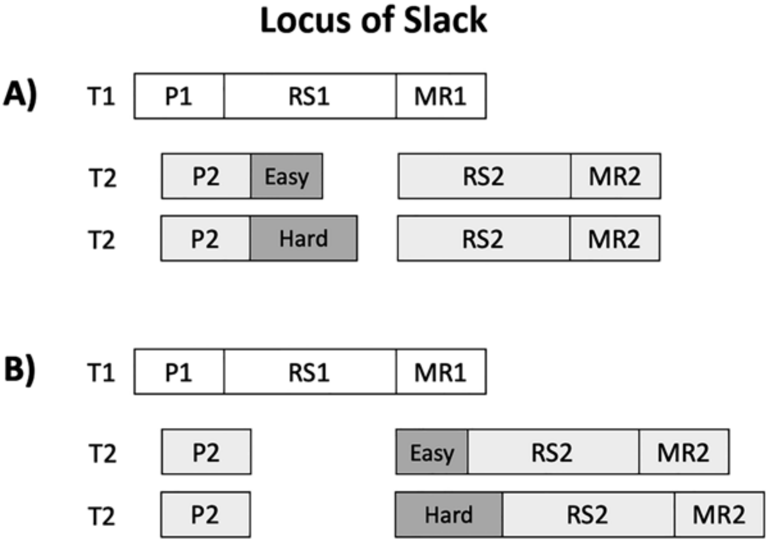

Fig. 2 In the locus of slack logic, the duration of a cognitive process is manipulated in Task 2 (here: easy vs. hard). This manipulation is observable in RT2s with a long SOA (not shown). (**a**) With a short SOA, the difference in duration of easy vs. hard is concealed by the bottleneck. This results in an under additive interaction with SOA. (**b**) If the cognitive process is subject to the bottleneck (or motor stage), differences in RTs are evident with short *and* at long SOA, resulting in an additive pattern. *P* perception, *RS* response selection, *MR* motor response, *T1* Task 1, *T2* Task 2

When applying the locus of slack logic (Schweickert 1983), the manipulation yielding the RT effect of interest is implemented in Task 2 of a PRP experiment. Of particular interest is then whether SOA and the manipulation in Task 2 combine additively or interact underadditively, because this outcome is informative with respect to the location of the manipulated Task 2 processing stage in reference to the bottleneck. More precisely, if the manipulation lengthens the precentral stage of Task 2, the additionally required processing time simply extends into the cognitive slack, when SOA is sufficiently short. In this case, the effect is not observable in RT2s at a short SOA, but only at a long SOA—hence an underadditive interaction. If, in contrast, the RT2 effect is visible with the same size across all SOA levels, the manipulation affects either the bottleneck stage or the motor stage of Task 2.

In this case, the effect propagation logic can be used for further clarification. Now, the manipulation of interest is implemented in Task 1, and usually the task order is simply reversed, that is, the previous Task 2 becomes Task 1 and vice versa. If the manipulation affects the motor stage, it should only become visible in RT1s, but not RT2s, because the motor stage proceeds in parallel to Task 2 processing. Any prolongation of Task 1 processing stages prior to or at the response selection bottleneck, however, should not only increase RT1, but prolong RT2 to the same degree, because differences in pre-bottleneck stage or bottleneck stage durations in Task 1 will automatically delay the start of the response selection stage in Task 2 by the same amount.

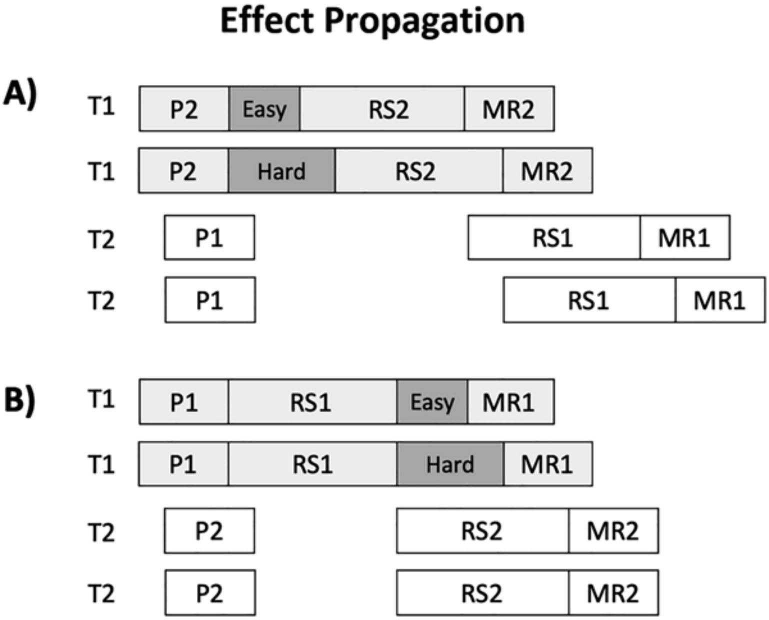

Fig. 3 In the effect propagation logic, the duration of a cognitive process is manipulated in Task 1. (**a**) If this process is located at the pre- or bottleneck stage, the difference in duration will fully propagate into Task 2 and can be observed in RT2s as well. (**b**) If the manipulation is located after completion of RS1, i.e., within the motor stage, the effect will not propagate into Task 2 and thus not affect RT2s. *P* perception, *RS* response selection, *MR* motor response, *T1* Task 1, *T2* Task 2

Pashler and Johnston (1989), for example, manipulated the difficulty of the perceptual stage by varying the intensity of a visual S2. Differences between easy and hard stimulus encoding conditions were exclusively observed at a long SOA when critical processing stages did not overlap. At short SOA, however, no difficulty differences were observed (see also De Jong 1993; Hein and Schubert 2004; Janczyk 2013; Paelecke and Kunde 2007; Pashler 1984). This underadditive interaction suggests that the additional processing time in the hard stimulus encoding condition is absorbed into the cognitive slack, and it provides support for the RSB assumption that pre-central processes can proceed during Task 1 bottleneck processing.

In contrast, if a (difficulty) manipulation affects the duration of the capacity-limited stage of processing, an additive combination of SOA and the manipulation is observed. For example, McCann and Johnston (1992) manipulated the duration of central response selection stages in Task 2 by employing an S-R compatibility manipulation in Task 2. As one would expect, the extended processing duration in the difficult incompatible S-R condition (compared to the easy compatible S-R condition) was observed irrespective of SOA. This result is in line with relating the capacity-limited stage with processes of response selection in Task 2 that cannot proceed in parallel to the response selection processing in Task 1 (Carrier and Pashler 1995; McCann and Johnston 1992; Pashler and Johnston 1989; Ruthruff et al. 1995; Schubert 1999).

Within the constraints of the stage-processing framework, the RSB model and the just mentioned techniques not only provide a window into the microstructure of dual-task processing but also offer a research tool that allows to determine the locus of specific cognitive processes (Pashler 1994, provides a detailed description of these predictions). Not surprisingly, there exists a plethora of published studies that successfully applied these tools over the years, and we will come back to some of these in a later part of this chapter (Bausenhart et al. 2006; Durst and Janczyk 2018; Fischer et al. 2007; Fischer and Schubert 2008; Janczyk 2013; Janczyk et al. 2019; Lien and Proctor 2000; McCann and Johnston 1992; Miller and Reynolds 2003; Oriet et al. 2005; Pashler and Johnston 1989; Schneider et al. 2020; Schneider and Janczyk 2020; Schubert 1999; Schubert et al. 2008).

The analogy of a cognitive bottleneck to a neural refractory period implies an all-or-none access to the bottleneck, with the consequence that central cognitive processing in Task 2 cannot proceed during Task 1 bottleneck processing. Although the term "central" processing is notoriously underspecified and has to be handled with care,[3] the totality of a Task 2 processing interruption has become subject to doubts. The same locus of slack logic that was used to provide evidence in favor of the RSB model has also been applied to test whether Task 2 processing of particular tasks can proceed in parallel to the Task 1 central processing bottleneck. Schumacher and colleagues (Schumacher et al. 1999), for example, combined a visual-manual task (Task 1) with an auditory-manual task (Task 2). SOA and response selection difficulty (2 S-R pairs vs. 4 S-R pairs) was varied in Task 2. Participants performed this dual task in two sessions, and a reward pay-off matrix was established. Importantly, however, the difference in RT2s, that is, the empirical sign of different Task 2 response selection difficulties, was considerably smaller at short compared to long SOA, thus yielding an underadditive interaction between SOA and the difficulty manipulation. In a similar vein (yet without extra practice and reward system), several studies demonstrated that significant semantic processing in Task 2, such as the activation of valence category information (Fischer and Schubert 2008) or the activation of numerical size information (Fischer et al. 2007; Oriet et al. 2005), can proceed during Task 1 bottleneck processing. In Fischer and Schubert (2008), for example, a tone categorization task served as Task 1 and an Eriksen word flanker task was implemented as Task 2. For the latter, participants were required to categorize positively and negatively valenced central target words (e.g., to kiss vs. to hate) as either pleasant or unpleasant with manual responses and to ignore above and below presented emotional distracter words. Target valence had to be categorized either in compatible target and flanker pairings (target and flanker belong to the same category—easy condition) or in incompatible pairings (target

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[3] The term "central" is an umbrella term that has its roots in the discrete stage logic of information processing and is meant to represent cognitive processing that should be distinguished from more peripheral perceptual and motor processing. Although the majority of studies with PRP experiments, cognitive processing at a "central" stage is not limited to response selection processes, but as aforementioned entails, among others, also various memory processes such as encoding, consolidation, or retrieval.

and flanker belong to opposite categories—difficult condition). Most importantly, the respective difficulty manipulations in semantic processing yielded again an underadditive interaction with the SOA manipulation. According to the locus of slack logic, these observations of underadditivity suggest that central Task 2 information processing proceeded during the central bottleneck (i.e., was absorbed into the cognitive slack) thus questioning the totality of processing interruption of Task 2 processing.

To sum up, for about 40 years, the PRP approach and the RSB model have stimulated and advanced theoretical and empirical dual-task research and research on attentional limitations in an unprecedented way. The attractiveness of the mental chronometry in the PRP approach is that it allows for the temporal sequencing of mental processes with response latencies and response accuracy being assessed separately for each task in discrete trials. Systematically varying the temporal overlap between tasks in the range of milliseconds enables an exact elaboration of dual-task load. In addition, the overall success and dominance of the approach and its underlying stage-processing framework is grounded in its clear predictions and their testability that stimulated theory-building (for an overview of predictions, see Pashler 1998). Together, PRP experiments appear to not only promise a valuable tool to study the microstructure of dual-task interference but has also been utilized to study effects of strategic task processing (Lehle and Hübner 2009; Miller et al. 2009; Plessow et al. 2017), task processing order (Ruiz Fernandez et al. 2011; Sigman and Dehaene 2006; Szameitat et al. 2006), effects of hierarchical task organization (Hirsch et al. 2018), inter-response dependencies such as response grouping (Borger 1963; Ulrich and Miller 2008), susceptibility to cognitive load (Fischer et al. 2010, 2011), or cognitive processing abilities in neurological and clinical conditions (e.g., Beste et al. 2018; Trikojat et al. 2017).

The PRP approach has also stimulated the development of refined experimental techniques, such as prioritized processing (PP) to study RSB-like dual-task limitations in a more simplified design (Miller 2017; Miller and Durst 2014, 2015; Mittelstädt and Miller 2017). The crucial difference to PRP experiments is that in PP experiments, the two tasks are never performed at the same time, that is, two stimuli are presented, but only one task is performed in each trial. In more detail, one task is defined as the prioritized task, and whenever this task requires a response (i.e., go trial), the secondary background task is to be ignored. Only in conditions, in which the prioritized task does not require a response (i.e., no-go trial), the background task is to be performed. Crucially, even in conditions without a response in the prioritized task, Task 2 response selection is delayed until the respective go/no-go response selection bottleneck in Task 1 is finished. Most of the predictions of the RSB model have been shown to extend to the PP paradigm (see Miller and Durst 2015, for a systematic comparison), which potentially allows using PP experiments to investigate processing limitations without RSB-typical factors, such as response grouping or strategic task component scheduling (cf. Miller 2017; Miller and Durst 2015).

4 Content-Dependent Dual-Task Costs: The Role of Crosstalk Between Tasks

The RSB model originally proposed not only an all-or-none bottleneck access but also rather independent processing of both tasks. Research on discrete dual-task performance, however, has accumulated evidence that dual-task costs do not necessarily reflect a direct consequence of the duration of central stage processing, but may be the result of processing interactions between two tasks (so-called crosstalk). In fact, some researchers see the potential interference between tasks as the major determinant of the limitation in dual-task performance (Duncan 1979; Navon and Miller 1987). This seems to correspond with our everyday experiences. For example, when performing a task (e.g., talking to a colleague on the phone), we often simultaneously engage in an additional task (e.g., checking an incoming e-mail), only to realize that additional task processing interferes with our primary and prioritized task (i.e., phone conversation).

There are two types of crosstalk that need to be distinguished (for a more extended discussion, see also Hazeltine et al. 2006): The first type of crosstalk emphasizes a transmission of information from one task to the other, especially during critical central processing. Crosstalk arises when both tasks share dimensional feature overlap, that is, either stimulus/response codes or the S-R translation process interacts with respective processes in the other task. For example, the semantic content between the e-mail and the phone conversation might overlap. As another example for discrete dual-task studies, categorizing the number 3 as smaller than five in one task typically interferes with the categorization of another number 7 as larger than five in another task, because both numbers activate different response categories, that is, "smaller than five" in the first and "larger than five" in the second (Fischer and Hommel 2012; Fischer et al. 2007; Hommel et al. 2016; Logan and Schulkind 2000; Oriet et al. 2005). Importantly, crosstalk denotes an interference measure that indicates parallel processing in the sense that the mere existence of crosstalk is evidence that significant processing can proceed during/in parallel to the capacity-limited response selection bottleneck. Thus, crosstalk is evidence for parallel processing. We will elaborate on this type of crosstalk in more detail below (see also Brüning, Koob, Manzey, & Janczyk, 2022).

The second type of crosstalk is not based on stimulus/response feature overlap or the activation of the same semantic response categories. Instead of an unwanted information transmission between tasks, here crosstalk arises because the same representational modality is accessed in both tasks (e.g., Feng et al. 2014). Thus, crosstalk between talking on the phone and checking an e-mail may arise because both, speaking and reading, require the vocal modality. Put differently, the mere pairing of the input-output modality in dual tasks determines how two tasks interact when performed together (Hazeltine et al. 2006; Ruthruff et al. 2006). Importantly, crosstalk again indexes an interference measure and thus marks dual-task costs. In this context, however, parallel processing refers to processing of two tasks without any dual-task costs. Put differently, in order to show true parallel and interference-free processing, crosstalk needs to be avoided.

4.1 The Role of Input and Output Modality Pairings

As already mentioned, the PRP effect and dual-task costs in general are quite robust. Examples for a reduction or (putative) elimination of these costs have been reported from training studies (e.g., Hazeltine et al. 2002; Liepelt, Strobach et al. 2011; Ruthruff et al. 2001; Schumacher et al. 2001; Tombu and Jolicoeur 2004) or for particular response systems, such as eye movements (e.g., Pashler et al. 1993) or reflexive eye blinks (Janczyk et al. 2014). Despite intensive research, most results and their interpretations are somewhat controversial, and the working mechanisms and conditions to achieve dual-task cost reductions are still debated (e.g., Ruthruff et al. 2003; Schubert and Strobach 2018; Strobach and Schubert 2017; see also Chap. 8 in this volume). Yet, a factor for a maximum reduction of dual-task costs was often less the amount of practice per se, but rather the application of specific tasks and task combinations (see, e.g., multiple resource theories, Navon and Gopher 1979; Wickens 1984). For example, dual-task costs are sometimes reduced or absent when both tasks are ideomotor compatible (Greenwald and Shulman 1973; Halvorson et al. 2013; Maquestiaux et al. 2020) or require distinct modality-based systems (Halvorson and Hazeltine 2015). Especially the role of input and output modality paring in both tasks has been highlighted to generally determine the extent of dual-task costs (e.g., Hazeltine and Ruthruff 2006; Hazeltine et al. 2006; Liepelt, Fischer et al. 2011; Ruthruff et al. 2006; Stelzel and Schubert 2011). Dual-task costs appear smaller, when a standard or compatible stimulus-response modality pairing is applied (e.g., auditory-vocal and visual-manual) compared to when a non-standard or incompatible modality pairing is applied (e.g., auditory-manual and visual-vocal). It has been argued that binding within one modality domain is more natural and less resource demanding than binding stimuli and responses across modality domains (Ruthruff et al. 2006). Extending this view, Göthe et al. (2016) argued that the specific pairing of S-R modalities may be less critical for dual-task costs than the pairing of relevant stimulus and response features in a shared (e.g., spatial) domain. That is, stimuli and responses are bound together and are represented in a common representational domain, which forms the basis of dual-task costs. In their training study, feature pairings and S-R modalities were varied independently. Most importantly, in compatible feature pairings, dual-task costs were virtually absent after practice irrespective of the modality pairing.

In general, these findings demonstrate that performance limitations in dual tasks are largely content-dependent. A central bottleneck seems thus determined by modality pairings and feature code overlap (see also Huestegge and Koch 2013; Huestegge et al. 2014).[4]

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[4] For recent neural network approaches for modeling dual-task costs on the basis of shared or multiple use of representations, see Feng et al. (2014) and Musslick and Cohen (Musslick and Cohen 2019; Musslick and Cohen 2021).

4.2 Backward Crosstalk as a Marker of Between-Task Interference

As aforementioned, crosstalk on the basis of dimensional feature overlap describes the situation that information processing in one task often critically affects information processing in another task. This risk of such between-task interference is particularly prevalent with (1) high temporal proximity between two tasks and (2) high dimensional overlap between tasks, that is, high tasks similarity (e.g., playing two different rhythms on a drum set). In general, crosstalk effects can be observed in both tasks: Task 2 processing can be affected from Task 1 processing, but Task 1 processing can be affected from Task 2 processing as well. The latter observation has been termed "backward crosstalk effect (BCE)" and is incompatible with the notion of an all-or-none bottleneck and entirely independent response selection-related processing of both tasks.

In a seminal study, Hommel (1998) had his participants to respond in Task 1 with manual left and right button presses to the color of a presented letter (H or S). Task 2 responses were verbal utterances to the identity of the same letters, for example, saying "left" to one (e.g., H) and "right" to the other letter (e.g., S). A compatibility relation was defined based on the dimensional overlap between the two S-R translation processes: A trial was compatible when the spatial codes of both responses corresponded (e.g., pressing the left key for Task 1 and saying "left" in Task 2) and were incompatible when they did not correspond (e.g., pressing the left key for Task 1 and saying "right" for Task 2). The most interesting result was that even RT1 was shorter in compatible than in incompatible trials: the BCE. Importantly, this interference transmitting from an S-R translation process in Task 2 to affect S-R translation in Task 1 occurs at a time point at which the response selection process in Task 1 is not yet completed, that is, during the response selection bottleneck. In other words, Task 2 response features are activated, while response selection in Task 1 is still underway. Similar results have been obtained with other types of dimensional overlap and responses (e.g., Ellenbogen and Meiran 2011; Fischer et al. 2007, 2014; Gottschalk and Fischer 2017; Hommel and Eglau 2002; Janczyk 2016; Janczyk, Pfister, Hommel and Kunde 2014; Koch 2009; Logan and Schulkind 2000; Renas, Durst and Janczyk 2018; Watter and Logan 2006; and many others), but also effects of Task 2 on Task 1 processing without obvious dimensional overlap have been reported (e.g., Miller 2006; Miller and Alderton 2006; see below). Therefore, the BCE measures the amount of between-task interference and has often been taken as a marker for efficient shielding and protection of Task 1 processing from interference of simultaneous Task 2 processing. Little between-task interference, for example, is reflected in a small BCE, indicating strong Task 1 shielding and/or efficient inhibition of Task 2 activation (see below and Fischer and Plessow 2015, for a review).

Evidence that central Task 2 information processing affects Task 1 processing prior to the completion of Task 1 response selection is obviously incompatible with a strict processing bottleneck in the original RSB model. Instead of refuting the

RSB model, however, a prominent refinement suggested a subdivision of the response selection stage into early and parallel operating *response activation*, the stage during which crosstalk arises, and a subsequent serially operating *response selection process* that is assumed to be capacity limited (Hommel 1998; Lien and Proctor 2002; Schubert et al. 2008). This conception saves the central bottleneck idea, but can subsume the occurrence of crosstalk as well.

So far, we have only considered BCEs based on dimensional overlap and compatibility between task features. Recent research highlights that such compatibility-based BCEs must be distinguished from other kinds of BCEs that appear to differ qualitatively. The most well-known example is the no-go BCE, first demonstrated by Miller (2006). In this case, Task 2 is a go/no-go task, and RT1s are shorter when Task 2 is a go compared with a no-go trial. As there is no obvious dimensional overlap, Miller suggested that inhibition required to overcome a prepared Task 2 response in no-go trials spills over to Task 1 and thereby lengthens the corresponding RT1s. Further examples, though having received less research so far, are influences of Task 2 response force (Miller and Alderton 2006) or Task 2 response distance and duration (Ruiz Fernández and Ulrich 2010).

Given the various appearances of BCEs and their accompanying explanations, recent research aimed at demonstrating empirical dissociations and at localizing processing stages responsible for their emergence. As mentioned above, the first account for the compatibility-based BCE suggested a distinction of central processing into automatic response activation and capacity-limited response selection (Hommel 1998; Lien and Proctor 2002), a distinction that has received much attraction, as it can nicely account for further patterns of underadditivity in PRP experiments (e.g., Paelecke and Kunde 2007). At the same time there is surprisingly little evidence of locating the BCE specifically to a response activation stage. Instead, recent studies have attributed the locus of the compatibility-based BCE more specifically to the response selection stage proper. For example, Thomson et al. (2015) exploited the fact that dual-task training shortens the capacity-limited central stage of processing and demonstrated that the BCE becomes smaller with training. Thus, they concluded that the BCE has a locus in the capacity-limited stage of response selection proper, rather than in a preceding stage of response activation. This conclusion receives further support from a study by Janczyk, Renas, and Durst (2018), who employed the locus of slack logic and the effect propagation logic to pinpoint the locus of the compatibility-based BCE. The results of this study support a locus within the capacity-limited stage of processing, but not a parallel stage preceding it, such as response activation. In addition, recent work has begun to employ mathematical modeling to investigate BCEs. The diffusion model (Ratcliff 1978) can be used to disentangle cognitive processes in binary decision tasks (for recent reviews, see Ratcliff et al. 2016; Voss et al. 2013). Briefly, the model assumes that information is accumulated until a *threshold* is reached and a response is selected. This accumulation is composed of the *drift rate* parameter, reflecting the speed of accumulation, and added noise modeled as a Brownian motion. Thus, threshold and drift rate combined can be taken to represent the selection of a response. In addition, the duration of early perceptual processing and motor processes is captured by the *non-decision time* parameter (for an application and more information, see Janczyk and Lerche 2019). The compatibility-based BCE was indeed related to the drift rate parameter in recent studies (Durst and Janczyk 2019; Janczyk, Mittelstädt and Wienrich 2018).[5] This work was recently extended in a study by Koob, Ulrich and Janczyk (2021). These authors explicitly modeled a controlled response selection process in Task 1 and a parallel-running response activation process in Task 2. Both resulting activations were superimposed in their extended diffusion model to determine the selected response in Task 1. When the automatic activation increased monotonically, but against an asymptote, the model did well in fitting empirical data from multiple studies. This study also addressed the question whether Task 2 response selection benefits from the already gathered activation. The tentative answer from data fitting and qualitative simulation is, however, that Task 2 response selection does not benefit (see also Schubert et al. 2008). If anything, Task 2 received a head-start toward the response given in Task 1 (see also Logan and Gordon 2001; Naefgen et al. 2017).

For the no-go BCE, it was proposed that inhibition required to abort a response in a Task 2 no-go trial spills over to Task 1 and slows the execution of its response (Miller 2006). This would suggest a locus of the no-go BCE within the Task 1 motor stage. Durst and Janczyk (2018) used the locus of slack logic and the effect propagation logic and indeed reported results favoring the Task 1 motor stage as the locus of the no-go BCE. In addition, this type of BCE was related to the non-decision time parameter in the diffusion model (Durst and Janczyk 2019). Conceivably, the assumed inhibition in no-go trials requires that the go-response is prepared to some degree. Durst et al. (2019) tested this in a situation where Task 2 was a choice/no-go task, that is, one with two possible go-responses. If both responses were equally likely, none of the responses would be prepared and, in this case, the no-go BCE was even reversed: RT1s were shorter in Task 2 no-go trials (see also Janczyk and Huestegge 2017). In contrast, when one response was more frequently required—and would thus benefit from advanced preparation—the typical no-go BCE was observed again.

In sum, the studies reviewed above make a strong case that compatibility-based and no-go BCEs are qualitatively different as they have different loci in Task 1 and likely also different sources in Task 2 processing (see Fig. 4). At the same time, it should be acknowledged though that these characterizations are far from being

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[5] The aim of localizing the compatibility-based BCE at either an automatic response activation or a subsequent capacity-limited response selection stage rests on the assumption of distinct and separable processing stages. Indeed, figural illustrations often show a distinct response activation stage that is followed by a subsequent response selection stage (e.g., Lien and Proctor 2002; Schubert et al. 2008). However, one may also think of response selection as a processing stage that entails two processes that start at the same time. A fast and automatic response activation process accumulates evidence in favor of a certain response. A slower response identification process verifies the correctness of the accumulated evidence and needs to intervene if the activated response does not match the required response (see Kornblum et al. 1990). Importantly, response activation and response identification do not necessarily form separable subsequent processing stages in that conception, but their interplay determines the duration of response selection.

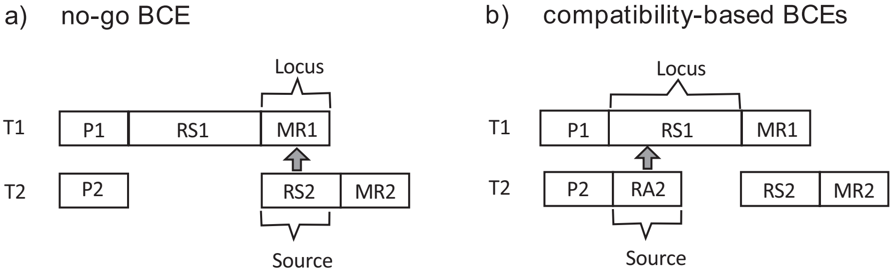

Fig. 4 Illustration of the locus and the source of the (**a**) no-go BCE and the (**b**) compatibility-based BCEs (*P* perception, *RS* response selection, *RA* response activation, *MR* motor response). Figure adapted from Durst & Janczyk (2019).

settled entirely. Regarding the no-go BCE, Röttger and Haider (2017) favored an account very similar to the case of the compatibility-based BCE, just with more abstract compatibility relations. For example, a “go-representation” in Task 1 might be incompatible with a “no-go representation” in Task 2 and thus impede Task 1 responding. Furthermore, electrophysiological studies used the lateralized readiness potential (LRP) and pinpointed the locus of the BCEs prior to the completion of central bottleneck processing (Ko and Miller 2014; Lien et al. 2007). For the no-go BCE, for example, Ko and Miller (2014) showed that central Task 2 processing affected the time between the onset of S1 and the onset of the stimulus-locked LRP in Task 1, suggesting that Task 2 selection-related processes in a no-go trial impacted on Task 1 prior to completion of Task 1 response selection. Finally, there is evidence that no advanced preparation of a response occurs in situations when go- and no-go trials occur with the same frequency (see Wessel 2018). This would certainly question the explanation of the no-go BCE in terms of overspilling Task 2 inhibition. As pointed out above, these findings highlight the requirement of further investigation.

5 Cognitive Control Demands and the Possibility of Adaptive Dual Tasking

The assumption of a structural bottleneck underlying dual-task costs (as in the RSB model) renders individual dual-task performance insensitive to changing situational demands and varying task characteristics and may have difficulties to account for recent observations of adaptive and strategic dual-task performance (Fischer and Plessow 2015). This is an important notion, because assuming a structural limitation in the cognitive architecture raises a rather pessimistic view on possibilities of training protocols and performance strategies to optimize individual dual-task abilities (Anguera et al. 2013; Miller et al. 2009; Strobach and Schubert 2017).

Recent research has highlighted that especially cognitive control functions are subject to performance optimizations in dual-task training protocols (Dux et al. 2009; Schubert and Strobach 2018; Strobach et al. 2014). Performing two tasks at the same time requires typical cognitive control functions known from single-task performance, such as maintenance and updating, shifting, and interference control (Miyake et al. 2000). In dual tasking, additionally the representations of two task sets need to be maintained and updated (upon Task 2 onset), and the engagement in task component processing needs to be shifted between both tasks eventually. Furthermore, assumptions of strategic task scheduling or capacity sharing between tasks beg the question of how task component processing is coordinated and capacity is flexibly allocated (cf. Fischer and Plessow 2015; Koch et al. 2018). Accordingly, some dual-task theories emphasize an involvement of further dual-task-specific cognitive control processes to manage flexible task component processing, to grant access to bottleneck processing, or to allocate capacity between tasks (e.g., Logan and Gordon 2001; Meyer and Kieras 1997). Similarly, recent studies targeted dual-task-specific control demands that comprised, for example, the monitoring for conflicts in dual tasks (Schuch et al. 2019), the simultaneous task-specific and task-unspecific adjustments to errors in a dual-task situation (Steinhauser et al. 2017), as well as the management of task-order control (Hirsch et al. 2017; Kübler et al. 2018; Luria and Meiran 2003).

Not surprisingly, recent functional neuroimaging studies show neural activity in brain regions during multitasking that are also typically associated with cognitive control functioning (Dux et al. 2006; Garner and Dux 2015; Marois and Ivanoff 2005; Schubert and Szameitat 2003; Stelzel et al. 2009; Szameitat et al. 2006; Tombu et al. 2011; Yildiz and Beste 2015). Further, causal involvement of control-related regions in dual-task performance was provided by recent brain stimulation studies (Filmer et al. 2013, 2017; Hsu et al. 2015, 2017; Kübler et al. 2019; Strobach et al. 2015; for a more detailed discussion, see Chaps. 6 and 7).

5.1 Instruction-Based Regulation of Cognitive Control in Dual Tasks

As aforementioned (Sect. 2.2.3), ECTVA is a theoretical model of dual tasking that emphasizes cognitive control involvement in terms of cognitive control parameters that ensure correct dual-task processing (e.g., task-set shifting, avoiding response reversals, etc. pp). A core assumption within ECTVA is that these control parameters are classically set in a top-down fashion by means of instructions. For example, an instruction-induced prioritization of Task 1 over Task 2 facilitates the reduction of interference from additional Task 2 processing (i.e., decreased BCEs). It results in a serial task processing strategy with most resources being allocated to Task 1 processing. Such an instructed proactive control state of Task 1 shielding, however, is effortful and resource consuming (Lehle et al. 2009). As a consequence, serial processing is often avoided when no priority instruction is given (Lehle and Hübner 2009) or when available resources are limited. Plessow et al. (2012), for example, showed that stressed compared to non-stressed individuals displayed reduced task shielding as indexed by increased between-task interference (larger BCE) in a dual task following an acute stress experience. Assuming that acute stress binds resources otherwise needed for task execution (Hockey 1997), increased interference may reflect a compensatory shift toward a more resource-saving processing strategy (e.g., reduced Task 1 shielding) to deal with the stress experience. Alternatively, acute stress might negatively impact on cognitive control functions (Arnsten 2009) and, thus, impair the cognitive control mechanisms underlying Task 1 shielding. To test these assumptions, Plessow et al. (2017) implemented block-wise instructions to up- or downregulate the degree of Task 1 shielding (see also Lehle and Hübner 2009). Results demonstrated that stressed individuals have control over the extent of between-task interference, as they were able to increase or relax Task 1 shielding according to the received instruction in the same way as non-stressed individuals (Plessow et al. 2017). These findings speak against an impairment of Task 1 shielding mechanism under acute stress in dual tasks, but generally favor the assumption of a stress-induced adjustment of cognitive control (Möschl et al. 2017; Plessow et al. 2011, 2012).

An instruction that sets cognitive control parameters, as suggested by ECTVA, should be especially effective at the beginning of an experiment, when the instruction is being implemented. Fischer et al. (2018) instructed a prioritization of Task 1 over Task 2. As expected, between-task interference measured with the BCE was small at the beginning, but continuously increased over the course of the experiment, which might indicate that individuals engage less in proactive control and thus relax the degree of Task 1 shielding over time. Importantly, introducing the prospect of reward instantly re-instantiated proactive Task 1 shielding. The BCE was substantially smaller in reward blocks compared to no-reward blocks that were presented in alternating order. In a final between-group comparison, the steady increase of the BCE over time was replicated in a no-reward group, whereas the BCE remained constantly small in the reward group. The stable size of the BCE suggests that the reward group maintained the same high levels of Task 1 shielding throughout the entire experiment. These findings demonstrate that not only direct instructions (Lehle and Hübner 2009; Plessow et al. 2017) but also motivational factors such as prospect of reward enable a dynamic regulation of cognitive control that defines the degree of between-task interference.

5.2 Context-Control Priming in Dual Tasks

In addition to top-down regulations of cognitive control resulting from instructions or reward, a bottom-up priming of cognitive control has received substantial consideration over the last years (for an overview, see Bugg and Crump 2012; Egner 2017). In the context of dual-task performance, this means that control parameters in ECTVA are not only adjusted by instructions but also by situational and contextual factors. Such factors typically relate to features of the task itself, such as variations in task difficulty (Fischer et al. 2007; Luria and Meiran 2005) or recent trial history. A prime example of such context-control priming is the utilization of experienced conflict for the upregulation of cognitive control (Botvinick et al. 2001; see also Dreisbach and Fischer 2015, 2016). This effect has also been observed in dual tasks, in which the experience of between-task interference results in a sequential modulation of the BCE (e.g., Janczyk 2016; Mahesan et al. 2021; Renas et al. 2018; Scherbaum et al. 2015; but see Schonard et al. 2020).[6] Similarly, the experience of dual-task errors triggers task-specific as well as task-unspecific processing adjustments (Steinhauser et al. 2017, for an overview see also Schuch et al. 2019). Not only the experience of conflicts, but also the frequency of significant task features can signal the need for control adjustments in dual tasks. It has been shown, for example, that the exposure to different SOA frequencies in different blocks (Miller et al. 2009), the frequency with which specific items predict short or long SOAs (Fischer and Dreisbach 2015), or the likelihood with which a location predicts the frequency of between-task conflict (Fischer et al. 2014; Gottschalk and Fischer 2017; Surrey et al. 2017) can be utilized to dynamically adjust cognitive control parameters in dual tasks and thus to bias processing to more serial versus more parallel processing (see Fischer and Plessow 2015, for a review).

In addition to characteristics of the dual task, control settings can be determined by dual-task unrelated contextual features. In a study by Fischer and Hommel (2012), for example, participants performed either a convergent (Mednick 1962) or a divergent (Guilford 1967) creative thinking task prior to a subsequent PRP experiment. It was hypothesized that the mere engagement in a cognitive task will form global meta-control states that can bias the local processing dynamics in the subsequent dual task. A convergent thinking task is associated with a systematic-focused and effortful in-depth cognitive processing, whereas a divergent thinking task is associated with a more holistic-flexible mode of processing. Accordingly, individuals that engaged in a prior convergent thinking task showed increased subsequent Task 1 shielding (reduced BCE) in the dual tasks compared to individuals that engaged in a divergent or in a more neutral thinking task. Similar priming of control states has been demonstrated by inducing different mood states prior to the dual-task episode. Here, individuals exposed to a negative mood induction protocol displayed a smaller BCE and thus stronger Task 1 shielding than individuals in a positive mood (Zwosta et al. 2013).

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[6] While many studies demonstrated (or at least assumed) that the experience of between-task interference triggers sequential modulations of the BCE, it is important to note that such sequential modulations were also observed when half of the previous trials did not provide a typical experience of between-task interference. Schonard et al. (2020), for example, reported sequential modulations of the BCE when the previous trial had a long SOA (i.e., 1000 ms). This is particularly interesting, because at such long SOAs, critical stages usually do not temporally overlap, and thus, no between-task interference should occur. The fact that sequential modulations of the BCE were nevertheless observed calls the immediate experience of between-task interference as the sole explanation of sequential modulations into question.

Finally, from an embodied cognition perspective, it has been argued that action components have a strong connection to perception and attentional control (Barsalou 2008; Fagioli et al. 2007). Stimuli presented near the hands (proximal stimulus-hand position) compared to stimuli presented far from the hands (distal stimulus-hand condition) appear to receive increased attentional control and thus preferential processing (Abrams et al. 2008; Davoli and Brockmole 2012; Liepelt and Fischer 2016; Reed et al. 2006). Fischer and Liepelt (2020) investigated the consequences of these effects in dual-task situations, in which two left and right located stimuli were presented in a proximal/distal relation to two respective response hands. More specifically, in a proximal stimulus-hand condition, both hands are located left and right at the monitor, whereas in a distal stimulus-hand condition, both hands are located beneath the desk. If the left and right hand at the monitor open a visual field with a wide attentional focus between both hands (Bush and Vecera 2014), interference between the two tasks (as indexed by the BCE) should increase. Alternatively, a proximal stimulus-hand position could lead to a stronger hand-specific attentional focus that facilitates processing of the stimulus nearest to the respective response hand. This hand-specific stimulus processing facilitates the separation of task representations and thus results in decreased BCE compared to the distal stimulus-hand condition. In two experiments, Fischer and Liepelt (2020) observed evidence for the latter prediction, demonstrating an embodied determination of between-task interference in dual tasks. Yet, no impact was found on the PRP effect (Hosang et al. 2018).

6 Future Perspectives

So far, we have discussed dual tasking limitations against the background that capacity limitations are related to response selection. Yet, what response selection is is often rather unspecified. Ideomotor theory highlights that actions are performed to achieve a certain goal, a perceptual change, often referred to as an *action effect* (Harleß 1861; see Pfister and Janczyk 2012, for a translation and discussion; see Shin et al. 2010, for a review). As a consequence, it is suggested that actions can—after associations between the respective bodily movement and the ensuing effect have been learned—only be selected by means of anticipating the desired perceptual state. In other word, action effect anticipation *is* response selection according to this view (for experimental evidence, see Janczyk et al. 2017; Janczyk and Lerche 2019; Koch and Kunde 2002; Kunde 2001; and many others). Against this background, Janczyk and Kunde (2020) suggested that simultaneous anticipation and maintenance of two effect representations is the limiting factor causing dual-task costs. Thus, they suggested to replace “response selection” in the model visualized in Fig. 1 with “effect anticipation” instead to highlight the source of the problems associated with dual-task interference. This view was backed up by results from various lines of research. For example, the compatibility relation yielding the compatibility-based BCE appears better characterized as compatibility of effects rather than effectors (Janczyk, Pfister, Hommel, and Kunde 2014; Renas et al. 2018). In other words, it does not matter so much whether the spatial location of the effectors is described as compatible, but rather (Task 1) performance is improved when the effects caused by using the effectors are compatible, irrespective of the effector (in)compatibility. In the same vein, the interplay of mental and manual rotations appears also to be driven by the rotational directions of the effect caused by the manual rotations, rather than of the manual rotation as such (Janczyk et al. 2012). A further line of evidence is that monitoring the actual occurrence of previously anticipated action effects contributes to dual-task costs (Kunde et al. 2018; Wirth et al. 2018). Thus, it appears as if the anticipated effect representation is maintained until the effect actually occurs, perhaps to check for success of the performed action. In sum, this view highlights a previously neglected contribution to dual-task costs and may help to better describe the architectural limitations.

7 Conclusion

The study of discrete dual tasks has provided the grounds for an extensive investigation of dual-task costs. In particular, a number of theoretical models have been developed in order to characterize the nature of dual-task costs and to specify their underlying causes. Although the RSB model is still prevalent in the dual-task literature, recent research on discrete dual tasks has accumulated evidence that dual-task costs may reflect more functional rather than structural limitations of the cognitive architecture. Thus, it's less the duration of the central stage that determines dual-task performance but more so content-based factors of task pairings that give rise to crosstalk between tasks.

Despite its immense success in dual-task research, the assumptions of the stage-processing framework and the PRP logic in particular have not been undisputed. For example, the PRP paradigm and the conclusions that are derived from it critically depend on the assumption of discrete and sequential stage processing. However, it is an open question to which extent proposed processes necessarily comply with a conceptualization in discrete and separable processing stages (e.g., parallel running automatic response activation processes). The distinctness of processing stages and their strict seriality in order of processing are rooted in early information processing accounts. We started out with introducing the stage-processing framework as a particular strength of the PRP logic, as it formed the basis for its clear-cut and testable predictions. At the same time, the assumption of discrete stage processing has been criticized by theorists proposing a strong coupling between perception and action. Such assumptions can be traced back to the ecological approach by James Gibson (1979), but are also prominent in contemporary frameworks like the theory of event coding (TEC, Hommel et al. 2001), which has recently been applied to account for dual-task costs (Hommel 2020), as well as conceptions of grounded/embodied cognition (for overviews see Barsalou 2008; Shapiro 2019). In this respect, a combination of classical dual-task paradigms with action dynamic approaches using continuous mouse movement responses might offer new insights at which time points the execution in Task 1 is particularly vulnerable to interfering influences of Task 2 response programming parameters (Scherbaum et al. 2015).

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Multitasking During Continuous Task Demands: The Cognitive Costs of Concurrent Sensorimotor Activities

Leif Johannsen, Nathan Van Humbeeck, and Ralf Krampe

In recent years, public views on multitasking have gradually mutated from appreciation for an essential skill for meeting modern-day challenges to growing fears of dangerous habits undermining work efficiency, driving safety, learning and the quality of social interactions (Analysis 2020). This swing is most evident in debates sparked by research related to media-multitasking and excessive use of electronic media (Organization 2011) in adolescents and young adults. The concomitant mix of cultural pessimism and parental concerns has not benefitted the quality of the scientific debate, which is partly due to the lack of agreement on a definition what constitutes multitasking in the first place. Such a definition is necessary to delineate the processes involved in multitasking, their constraints and potential consequences. The most important constraints and consequences relate to the questions which combinations of tasks can be performed simultaneously and at which costs (the so-called dual-task or multitask costs).

Everyday parlance considers multitasking the concurrent performance of at least two activities. Scientifically speaking, this definition is little helpful because it shifts explanatory load to defining what constitutes "activities". Consider for a moment breathing, postural control, listening or holding a cup of coffee, all of which we perform concurrently with one another (and numerous other activities) during most times (breathing, postural control) or at frequent occasions in our daily lives. Most

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people would probably attribute a high degree of automaticity to these activities and not suspect interference with, for example, concurrent cognitive tasks unless unexpected events (e.g. a perturbation to postural stability) or changes in task demands (e.g. an important message uttered in a garbled voice while we were listening to chill-out music) occurred.

In the cognitive neuroscience literature, multitasking is considered the concurrent pursuit of two or more task goals (Koch et al. 2018). This definition has important implications. Goals are activated and maintained in the working memory (WM) system along with relevant information on how to achieve them or pointers to long-term memory (LTM) contents that allow retrieval of this information. So conceived, WM with its limited capacity is a prime candidate mechanism to determine task coordination costs.

In this chapter, we focus on multitasking settings in which at least one component is a continuous task. Continuous tasks as we perceive of them are permanently providing the individual with input, and they permanently allow for performance adjustments (behavioural output). This definition basically limits continuous tasks to certain types of sensorimotor activities, like postural control, movement timing and time perception, listening and speaking and visuomotor tracking. Note our characterization of tasks appeals to a phenomenal dimension, not a process distinction. Discrete (as opposed to continuous) tasks with defined stimulus presentation and response periods and precise indications of task switches also require continuous attention and performance monitoring. Likewise, we are not assuming that continuous tasks are permanently attended to with the same intensity, and we do not rule out switching or temporarily suspending one task at the cost of the other as critical processes.

We start out with a brief review of theories of multitasking before we turn to empirical evidence related to four domains: postural control, time perception and production, visuomotor tracking and listening and speaking. This selection of domains is somewhat arbitrary; however, it comprises a broad range of real-life skills and capabilities which have been thoroughly investigated. Rather than trying to be complete, we highlight studies that meet certain criteria which we explicate along with our description of theoretical frameworks. Two major themes will reoccur throughout the chapter echoing our main messages. First, multitasking effects related to continuous sensorimotor tasks have long been ignored or underestimated because they were considered non-cognitive and quasi-automatized due to extensive usage. However, such tasks exert substantial costs on concurrent, cognitive activities which are by no means limited to certain age groups or clinical populations. Second, while continuous tasks probably allow more degrees of freedom in attention allocation and switching compared with discrete tasks, their management in multitasking settings requires more flexibility on the part of the individual for optimal performance. As a result, individual differences in multitasking with continuous tasks must be considered a prime constraint for adaptation in real-life settings (Krampe and Baltes 2003).

1 Models of Multitasking

Traditionally, models of multitasking depart from the assumption of processing resources and related shortages during concurrent performances. *Bottleneck theory* assumes that making a decision such as selecting the correct response to a particular stimulus is a sequential process on a high central processing stage. Selection of the response cannot occur in parallel to other selection processes and therefore causes the so-called "psychological refractory period", a delay of the subsequent response (Pashler 1994). In addition to these central bottlenecks at the response selection stage, peripheral bottlenecks have also been suggested to occur at the response initiation stage to prevent the execution of the response in quick succession (De Jong 1993). One implication of *general-resource models* is that the same individual differences that constrain single-task performance determine dual-task performance. The critical test for this account is to evaluate age differences in dual- task performance after individual differences in single-task performance are statistically controlled for (i.e. by means of hierarchical regression analyses). For example, larger dual-task costs in older compared with young adults were greatly diminished or disappeared altogether when single-task performance was controlled for (Verhaeghen and Cerella 2002; Verhaeghen et al. 2003).

A second type of models emphasizes *limitations in task-coordination strategies or resource allocation* (Baddeley 2012). In the cognitive neuroscience literature, multitasking and allocation of attention to concurrent task demands are considered instances of cognitive control or executive functions. Cognitive control (we prefer this term over "executive control", which is more common in the working memory literature) involves multiple processes including working memory, inhibition, planning, task-set switching and allocation of attentional resources, all of which have been linked to prefrontal brain regions (D'Esposito and Postle 2015). Experimental studies as well as neurophysiological evidence indicate that these mechanisms and related regions are most sensitive in terms of age-related decline. One implication of the *cognitive control account* is that age-related differences in multitasking settings should be pronounced if one of the component tasks itself engages cognitive control operations. This was indeed demonstrated in a recent study by Meijer and Krampe (2018). These researchers systematically varied the cognitive control demands of a cognitive task (e.g. working memory storage or LTM retrieval) that young and older adults performed concurrently with a motor timing task. In line with the cognitive control account, dual-task costs and age-related differences therein increased with cognitive control demands.

A specific version of the allocation model trying to account for age-related differences in multitasking is the *cognitive compensation hypothesis* (Li and Lindenberger 2002). It argues that older adults compensate for declines in sensorimotor processing through resources that are normally dedicated to cognitive processing (Doumas et al. 2008; Krampe et al. 2011; Li et al. 2001; Lindenberger et al. 2000). The *cognitive compensation hypothesis* departs from the idea of age-related declines in processing resources as the key account for performance declines. The critical tenet is that sensorimotor processing in older adults is more cognitive in that they must allocate a relatively larger share of available resources to postural control, holding objects or timing movements than young adults. The cognitive compensation hypothesis itself does not specify the mechanisms underlying the observed age-differential allocation of resources.

Alternative goals motivate research into multitasking and the use of the dual-tasking method particular, in which a primary task under investigation is performed with the additional load of a simultaneous secondary task. One aim is to use multitasking as a methodology for testing limitations in human cognitive-motor flexibility. This approach is inspired by an ecological perspective, which considers of major interest the adaptation of humans to the demands of interactions with the environment. Especially, the context of continuous activities, motor and cognitive, illustrates a particular ecological validity, for example, as in activities such as balance control or listening, where ageing-related increases in susceptibility to multitasking interference may become most apparent in daily life. Another aim is to investigate multitasking to gain an understanding of the mechanisms that cause interference between simultaneous task processes, for example, the reasons why continuous activities, movement tasks in particular, may appear automatic and effortless in their execution but still influence and be influenced by cognitive processes. For the present chapter, we have selected four areas of research into continuous multitasking situations, where task interference and dual-tasking costs of been interpreted in the light of those previously stated theoretical accounts. We are going to argue that as the four task domains discussed in the following sections appear to be prime examples of automatic processing, the flexibility to adapt to changing task demands implies the involvement of high-order, capacity-limited processes for the purpose of state predictions and conflict resolution.

2 Multitasking Involving Concurrent Postural Control

The capability to control body balance in an erect posture against the pull of gravity is one of the defining milestones in human evolution. The versatility, flexibility and the degree of perfection that humans demonstrate in terms of controlling the multitude of postural degrees of freedom when keeping a stable balance during sitting, standing or diverse forms of bipedal locomotion, such as walking and running, is truly astonishing. Further, it is quite normal for us to engage simultaneously in combination of tasks, one of which requires balance control while the other demands some form of cognitive control, for example, reading a book in a standing posture or walking while holding a conversation or while checking your mobile phone. Standing or walking may feel effortless in such multitasking situations and the notion far-fetched that these motor activities interfere with any cognitive activity one is consciously engaged in. Balance control exemplifies by its nature a category of a continuous task due to the fact that an unstable load needs to be permanently controlled against gravity. The demand for balance control is virtually permanent, and in itself it is a process which cannot be stopped, probably not even by adopting a seated or supine posture, although postural responses and sway can be inhibited.

This section of our chapter will discuss aspects of sensorimotor integration for balance control and how these may require cognitive resources to meet the contextual demands of a postural task. Aspects of balancing expertise as demonstrated by athletes such as gymnasts, training aspects of cognitive-postural dual-tasking and developmental aspects will not be covered in this section. A central question is to what extent the control of body balance and posture are truly automatic processes governed by domain-specific, cognitive-impenetrable and autonomic information processing modules (Coltheart 1999; Fodor 1983). In other words, one needs to decide whether balance control occurs independently of general cognitive resources such as attention, is not susceptible to an individual's expectations or beliefs and is restricted only to very particular classes of sensorial stimulation. As we will see in the following, the notion of body balance control being a purely automatic process is quite unlikely.

2.1 Postural Control as a Continuous Motor Activity

Quiet upright standing, as an example of a simple, apparently static posture, is still a highly dynamic activity caused by the interaction between body displacement through gravity pull and opposing muscle-produced torque. The fact that the control of body balance depends on the current postural context, for example, changes in muscle activations in response to altered physical support situations (Horak and Nashner 1986), implies that it is very much a process, which relies on high-level representations of the body and its environment. This alone is an indication that the control of body balance cannot be an entirely automatic process based on conditioned reflex arcs as previously suggested (Magnus 1924; Sherrington 1906).

In order to better understand the nature of dual-task interference between the postural and cognitive domains, the difficulty of either the cognitive, the postural or both tasks was varied. Regarding the postural difficulty, manipulation of the standing posture (normal bipedal with wide or narrow stance width; semi- or full tandem Romberg stance or single-legged stance; Kerr et al. 1985; Lajoie et al. 1993; Teasdale et al. 1993), the support surface condition (wide or narrow; firm or compliant; fixed, tilting or oscillating), the availability and the disturbance of sway-related sensory feedback (with or without vision; with or without vibratory stimulation of the soles of the feet or galvanic vestibular stimulation; with or without sway-referencing of the visual environment or the support surface; Barin et al. 1997; Shumway-Cook and Woollacott 2000; Teasdale et al. 1993) or any kind of postural perturbation (mechanical force acting on the body; abrupt sensory change or transition within or between sensory states; Brauer et al. 2001; Brown et al. 1999; Rankin et al. 2000) was used to challenge the postural control system and to create an ad hoc ordering of difficulty levels. A benchmark for a systematic ordering of postural difficulty is still the computerized dynamic posturographic system implemented as the sensory organization test (SOT; Ford-Smith et al. 1995), which features six testing conditions assessing the situation-specific weighting of the visual, vestibular and somatosensory channels as well as the resolution of intersensory conflict between these modalities (Nashner 1997).

Cognitive tasks were chosen to target specific domains of cognitive functioning such as alertness, focussed or divided attention, working memory, executive function and decision-making, information processing speed, visual search, learning and memory of verbal or visual content, verbalization and verbal fluency and listening. Difficulty in cognitive task was varied by changing the signal to noise ratio, increasing the items of memory load or changing the tasks themselves (sensory modality; inhibitory demands) or by altering their processing complexity (storage and updating). The demand for attentional resources was often expressed by performance reductions in the cognitive task, such as increased response latency in reaction tasks, increased error proportions or lower recall in memory tasks. Performance in the postural task was most often judged by some kind of sway variability measure, including centre of pressure displacement (CoP) or CoP area.

2.2 Theoretical Models of Higher Cognitive Involvement in Postural Control

Theories of the fundamentals of postural control, which consider the involvement of cognitive resources in more explicit detail, are still rare and at best controversially discussed. The majority of studies using a dual-task methodology in the postural domain aimed to understand the nature and extent of cognitive resources shared by the control of body balance. Early findings suggested that interference between cognitive tasks and balance is domain-specific in that balance affects spatial but not verbal tasks. In order to test if body balance control requires cognitive resources a specific modality, Kerr et al. (1985) used the Brook's verbal and spatial working memory encoding and memorization tasks to demonstrate that body balance in tandem Romberg stance increases the number of errors in the spatial Brook's task in a dual-task situation compared to performance when seated or dual-task performance in the verbal Brook's task. It therefore seems that the demands of keeping tandem Romberg stance stable imposes an increased reliance on spatial working memory resources compared to sitting. Van der Velde and colleagues (2005) confirmed the notion that processes involved in spatial working memory with coordinative demands due to two-item load also interferes with the control of body balance in tandem Romberg stance.

Although balance effects on spatial task performance have been corroborated, other researchers have observed that simultaneous engagement in non-spatial secondary cognitive tasks and verbal memory tasks as well as mental arithmetic, articulation and counting can influence balance. Maylor et al. (2001) used the same Brook's memorization tasks as in Kerr et al. (1985) but with three levels of memory load as a processing difficulty manipulation. Maylor et al. (2001) reported performance decreases in the spatial working memory task irrespective of the difficulty level and in the verbal task in the highest level of difficulty only. Body sway in the dual-task condition was not systematically affected by the secondary task or its difficulty. That the nature of information processing during the secondary task influences the interference with balance control was also demonstrated by Ramenzoni et al. (2006). They observed that encoding and rehearsal of cognitive stimuli will show distinct interference patterns with balance control based on the stimuli's specific modality. A verbal task generates greater dual-task costs in the encoding phase while a visual task as stronger interference effect on the rehearsal phase. A possible confounding factor in these observations, however, could have been subtle differences in the visual fixation requirement of both phases (Ramenzoni et al. 2006).

Instead of varying the difficulty of a secondary cognitive task, other studies varied the difficulty of the postural task in order to probe the extent of general resource sharing between postural control and cognition. The demands of attentional resources increase when the difficulty and complexity of balance control increases. Lajoie et al. (1993) showed reduced performance in a secondary cognitive task, a verbal reaction task with an auditory probe signal, with increasing difficulty of a simultaneous postural task. Sitting resulted in the shortest latencies followed by standing and walking. A continuous variation in difficulty of one or other of the competing tasks might be less susceptible to criticisms of an ad hoc ordering of qualitatively different tasks in terms of their difficulty. Therefore, Barra et al. (2006) varied the difficulty of a secondary cognitive task (spatial and verbal Stroop paradigms) in terms of the duration of the interstimulus interval (ISI) of a number of successive stimuli, which had to be evaluated and counted during a single trial. Three levels of difficulty (shorter ISIs were more difficult) were combined in a factorial design with four levels of balance difficulty associated with reducing the width of the base of support. With this paradigm, Barra et al. (2006) found sway was reduced under dual-task conditions relative to a control condition.

Compared to steady-state balance control during quiet standing, balance stabilization following a mechanical perturbation is likely to impose transiently increased demands on general cognitive resources. For example, Rankin et al. (2000) imposed backward perturbations of the support base onto their participants while they were engaged in verbal mental arithmetic such as backward subtraction as a dual-task load. Electromyographic activity of the lower leg muscles was recorded as the major behavioural parameter. Muscle activity immediately following perturbation onset up to 350 ms later was not modulated by dual-task requirements. Activity within the period between 350 and 500 ms after perturbation, however, was reduced under dual-task load. The implication was that the immediate response to a perturbation happens in relatively automatic mode, while the later transition from a dynamic to steady postural state requires involvement of cognitive resources.

McIlroy and coworkers (Maki et al. 2001; McIlroy et al. 1999; Norrie et al. 2002) pursued the hypothesis that the demands on the postural control system vary during the stabilization period following a balance perturbation. Maki et al. (2001) concluded that the later stage of a postural response following a postural perturbation is dependent on attentional resources while the earlier phase is more automatic. In contrast, Redfern et al. (2002) demonstrated, however, that performance in an attention demanding task was reduced under dual-task load early after a perturbation. A follow-up study, combining sudden onset postural perturbations with a simple auditory reaction time task and visual cues indicating the direction of the perturbation, revealed that interference between the postural and reaction time tasks only occurred when the auditory stimulus was presented simultaneously with the postural perturbation (Muller et al. 2004). Possibly, the auditory distractor delayed detection of the perturbation.

While a mechanical balance perturbation requires an immediate motor response to stabilize the body, the addition or removal of noise to a specific sensory channel results in a disruption of the current sensorial organization. For example, bilateral vibratory stimulation of the ankle muscles induces background noise in the proprioceptive system, which deprives participants of reliable feedback about the state of the ankle joint. Teasdale and Simoneau (2001) used bilateral ankle muscle vibration to create transitions between states of sensory organization with and without reliable proprioceptive feedback in addition to transitions between states with and without visual feedback. To probe the attentional demands necessary for recalibration and adjustment of the sensory organization for postural control, they included a secondary auditory reaction task. In the absence of visual feedback, reintegration of lower leg proprioception into the postural control loop resulted in increased attentional demand as illustrated by longer response latencies (Teasdale and Simoneau 2001). Honeine et al. (2017) demonstrated that the integration of vision into the postural control loop and subsequent postural stabilization involves high-level attentional resources also engaged in backward counting, while dual-task load did not influence destabilization and sensory reweighting following vision withdrawal, which suggests greater automatization.

Conflicting evidence with regard to whether or not balance control is impaired by sharing processing resources with a cognitive task has been presented. If balance and cognitive tasks share common resources, increasing the difficulty of the cognitive task should reduce performance of the balance task and vice versa. In fact, the literature is inconsistent on this point. For example, reduction in sway was found with verbal reactions to visual and auditory stimuli (Vuillerme et al. 2000) and during silent backward counting (Andersson et al. 2002). While others reported an increase in sway during dual-task performance (Andersson et al. 1998; Pellecchia 2003), Maylor et al. (2001) found a reduction of sway compared to single-task standing during the memory encoding phases of the spatial and verbal Brook's tasks and an increase during the retention phase of the respective stimuli.

A possible interpretation of the inconsistent findings in the dual-tasking methodologies reviewed above is that the underlying relation between balance and cognition is not monotonic. These inconsistencies have been attributed to variations in the difficulty and complexity of processing of the various secondary cognitive tasks (Andersson et al. 2002; Dault, Frank, et al. 2001; Dault, Geurts, et al. 2001) as well as variation in the priorities assigned to balance and cognitive tasks (Mitra 2003; Mitra and Fraizer 2004) with older adults tending to give greater priority to balance (“posture first” principle; Brown et al. 2002). Also, Yardley et al. (1999) suggested that balance was perturbed through articulation and respiration required by a secondary task rather than by the cognitive demands. However, subsequently, separate effects of articulation and attentional load on balance control due to secondary task involvement were demonstrated (Dault et al. 2003).

As an alternative to a general resource competition account, Wulf and coworkers (McNevin and Wulf 2002; Wulf et al. 2004) suggested the “constrained action hypothesis”, which suggests that attempting to control one’s own swaying motion by consciously focussing attention on the motion itself will actually constrain the postural control system in its efficiency by interfering with automatic motor control processes that would normally be more dominant in balance regulation. Vuillerme and Nafati (2005) instructed their participants explicitly to attend to body sway and to increase active intervention into postural control. They observed that an attentional focus on body sway reduced the efficiency of postural control. Polskaia et al. (2015) extended these observations by demonstrating that postural stability improved when a cognitive task was performed in contrast to both an internal or external focus of attention and argued that a continuous cognitive task binds attention and therefore facilitates automatic control of posture. Subscribing to the constraint action hypothesis, Huxhold et al. (2006) proposed a dual-process account of interference between balance control and cognition. They found a U-shaped interference curve between balance and cognition in the sense that when cognitive task difficulty increased, body sway first decreased and then increased. In the first process, which operates when the secondary cognitive task is less demanding in terms of attentional resources, they suggested that by shifting attention away from postural control in a dual-task situation, light distraction by an easy cognitive task would facilitate the efficiency of largely automatic balance control mechanisms and inhibit less efficient voluntary balance adjustments. The second process was assumed to operate when the secondary task demands exceed an individual’s level of attentional resources and the resulting competition between balance control and the cognitive task for general resources leads to a reduction of postural stability.

2.3 *Ecological Aspects of Postural Control*

A central assumption from an ecological point of view is that humans actively search for information and that the postural control system purposefully generates sensory feedback to estimate the equilibrium state of the body (van Emmerik and van Wegen 2002). Riccio and Stoffregen (1988) proposed that exploratory behaviour is an important aspect of an adaptive organism to develop effective postural control strategies in a particular situation, for example, in conditions where the characteristics of the environment such as the support surface are changing. This would create conflicting demands for the postural control system to compromise between the generation of movements to explore the characteristics of the current action space and the generation of movements to keep the system stable within a specified region of the action space. In the domain of postural control, Riccio and Stoffregen (1988) demonstrated that active perception of body orientation is grounded on the perception of corrective actions required to keep a default (tilted) posture. They suggested that a trade-off between less effortful postural corrections when nearer the equilibrium point and more reliable interpretation of the forces acting on the body with greater deviation from the equilibrium point governs postural control. Riley et al. (1997) contrasted body sway dynamics during normal upright standing and forward leaning and concluded that the short-term dynamics of normal standing comprise a greater amount of exploratory behaviour due to the greater distance to the limits of stability. Ehrenfried et al. (2003) exposed upright standing participants to a wide optokinetic, chequerboard patterned flow field, which led to increased body sway with faster flow field velocity. Using Brook's spatial and verbal memorization tasks as secondary cognitive tasks, they observed reduced body sway in both cognitive task domains. They proposed that the sway reductions in the dual-task situations illustrate the presence of an attention-demanding process that explores postural stability within a specific environmental context. According to their rationale, the visual flow field reduced the reliability of visual afferences and consequently potential postural destabilization. Increased body sway would partly contain exploratory movements to assess body self-motion in a noisy visual environment. Ehrenfried et al. (2003) suggested that the dynamics of body sway express an active, attention-demanding probing of self-motion and the state of balance stability in the context of noisy and potentially disruptive sensory stimulation.

An extension of the ecological point of view with respect to interference between balance control and suprapostural tasks in a visual environment was provided by Stoffregen and co-workers (2000). Contrasting a visual search task with an inspection task and asking their participants to switch visual focus between two displays at different distances, they demonstrated that performing the visual search task resulted in reduced body sway (Stoffregen et al. 2000). Their assumption was that postural control takes part as a component of a purposeful perception-action coupling, so that body sway is actively modulated to assist in suprapostural tasks requiring oculomotor precision. A suprapostural task situation resembles a special case of hierarchical motor dual-tasking in which the control of body sway is recruited to serve the performance goal of a presiding task. Similar observations were also made when standing participants were required to perform with their eyes a visual smooth pursuit task (Stoffregen et al. 2006, 2007). Keeping precise light fingertip contact with an earth-fixed reference has also been considered to impose the demands of a suprapostural task leading to reductions in body sway when touch is a relevant task requirement (Riley et al. 1999). A comparison of dual-task interference effects with spatial and non-spatial cognitive tasks between quiet standing and a postural alignment task with visual prevision demands showed that cognitive distraction increased sway only in the quiet stance but not in the visuopostural alignment condition (Mitra et al. 2013). This observation contradicts the resource competition account as the visuopostural alignment task supposedly required more attentional resources than quiet standing. To explain the interference between cognitive task and balance control in in these situations, Bonnet and Baudry (2016a, b; Bonnet et al. 2017) proposed a model by which additional cognitive resources create a link between visual behaviour and postural control so that a synergistic unification of both task domains achieved by proactive sway reduction facilitates precision in the visual task.

An important aspect here is the functional interpretation of any observed reductions in body sway. Reduced sway could indicate increased postural stiffness, for example, due to joint-specific co-contraction of agonist and antagonist muscles, but it could also be the result of improved sensorimotor performance. McNevin and Wulf (2002) argued that performing a suprapostural task with an external attentional focus would distract from an implicit "standing still" instruction and thereby improve the effectiveness of automatic postural control with increased postural stiffness and reduced body sway as consequence. A similar conclusion that a sufficiently demanding secondary cognitive task will increase postural stiffness and reduce short-term exploratory behaviour was drawn by Vuillerme and Vincent (2006). On the other hand, Stins et al. (2011) compared postural sway dynamics and lower leg muscle activations in two dual-task situations to a situation, in which postural threat was induced by fear of heights and a postural stiffening strategy was considered most likely to occur. The regularity of sway dynamics differed between the dual-task conditions and the postural threat situation as well as a single-task control condition. They concluded that in the dual-task conditions, attention was distracted from sway control which resulted in reduced body sway but not due to increased postural stiffness (Stins et al. 2011).

With the ability to adapt the postural and locomotor control systems to the demands of an environmental situation, an intact central nervous system is required. Any neurological lesion or disease is likely to affect the optimal control of posture and balance. When either the peripheral or the central nervous system (CNS) is subjected to ageing-related degeneration or some form of injury or disease, the possibility of experiencing balance loss and the threat of subsequent physical harm from falling become serious factors causing anxiety and restricting autonomy and quality of daily living. Multitasking itself may become a threat to postural stability, so that an individual with impaired balance needs to choose which activity to prioritize at a certain moment in time.

2.4 Interindividual Differences and Age-Related Effects

Ageing has been suggested to alter the complexity of the human brain (Lipsitz 2002; Vaillancourt and Newell 2002), and it has been proposed that movement control in older adults becomes less automatic and more dependent on higher-level cognitive movement monitoring (Heuninckx et al. 2005). This might explain why postural stability becomes more susceptible to dual-task interference with increasing age and difficulty of a balance task (Lajoie et al. 1996; Maylor et al. 2001; Teasdale et al. 1993) as the amount of cognitive processing required for postural control depends both on the complexity of the postural task and on the capability of the subject's postural control system (Horak 2006). The influence of the nature and difficulty of the cognitive task on cognitive-postural interference was demonstrated by Lajoie et al. (2017), who contrasted in older adults the interference between postural control and discrete cognitive tasks with intermittent attentional demands of various difficulty levels against cognitive tasks with continuous demands. In the difficult discrete cognitive and the continuous cognitive dual-task situations of all difficulty levels, sway variability was reduced, which was interpreted as postural stiffening due to automatization of balance control.

Ageing may lead to a vicious circle of impaired balance performance, increased fear of falling and more compensatory, conscious control for balance in older adults. Older adults show diminished reliability of sensory input from somatosensory, vestibular and visual channels, which by itself has been suggested to result in increased postural instability and less efficient balance control. Consequently, it has been hypothesized that older adults rely more on visual information to control their body balance (Simoneau et al. 1999; Speers et al. 2002; Wade et al. 1995). Thus, an over-reliance on visual input for the control of body balance seems to correlate high with balance impairments in the ageing population (Anand et al. 2003; Sundermier et al. 1996). It was suggested that to compensate a general decrease of perceptual acuity in the vestibular, proprioceptive, auditory and probably even visual sensory domains, general attentional resources are suggested to be reallocated for compensation of the sensory decline (Shumway-Cook and Woollacott 2000). Less efficient balance control in the elderly could be also caused by a general slowing of both sensory and cognitive processing (Horak et al. 1989; Teasdale, Stelmach, and Breunig 1991; Teasdale, Stelmach, Breunig, et al. 1991), which results in an overall degradation of balance performance due to simultaneous higher-level cognitive and attentional factors sharing processing resources with multisensory integration and control of body balance.

Prioritization of the postural or cognitive domain is situation-specific and also depends on an individual's perceived consequences of a loss of balance. For example, Brown et al. (2002) positioned younger and older adult participants on a hydraulic platform and assessed body sway in a dual-task situation performing the Brook's spatial letter task under four conditions of perceived postural threat depending on height of the platform and proximity of stance position to the edge of the platform. Increased postural threat resulted in greater arousal with an added effect of dual-task instructions in both groups of participants. While the younger adults' body sway remained unaffected by the postural threat, they tended to perform faster in the cognitive task in the condition of greatest postural threat. Older adults in contrast demonstrated a remarkable reduction in body sway combined with slowing cognitive performance when postural threat increased (Brown et al. 2002). This result pattern exemplifies the principle of "posture-first" in older adults, according to which deterioration of performance in a cognitive task is accepted for the purpose of improving the control of postural stability by the reallocation of attentional resources. Bernard-Demanze et al. (2009) used complex measures of sway to demonstrate that dual-tasking costs are determined by the complexity of the postural task and that young adults solve the cognitive-postural interference problem by increased automation, which lead to performance benefits with cognitive distraction, while older adults preferred prioritization of the postural task and selection of a strategy to compensate for their performance limitations. More recently, Lajoie et al. (2017) demonstrated that not only the difficulty but also the specific neuropsychological processes engaged and the discrete or continuous nature of a secondary cognitive task influence the interference with postural control, especially in older adults.

Regarding perceptual perturbations to balance, Teasdale, Stelmach, Breunig, et al. (1991) found that older adults show increased balance fluctuations during upright stance when exposed to a sudden switch from a postural state without visual feedback into a state with visual feedback suggesting an impaired central integration of visual sensory information for reconfiguring the postural set. Simoneau et al. (1999) confirmed this by reporting that older adults are more susceptible to a sudden change of dynamics within the visual modality. Honaine et al. (2017) combined addition and withdrawal transitions in the visual modality with the dual-task demands of counting backwards and demonstrated that addition of the visual modality with dual-task load delayed onset of postural stabilization by 300 ms. As the withdrawal transition was not affected by the dual-task load, they suggested that more automatic, subcortical processes control the destabilization of sway, while a cortical supervisory process would control sway in the phase, when sway-relevant information had to be integrated in the postural control loop. Horak et al. (1989) hypothesized that older adults show a deficit for central sensory reweighting during changing environmental conditions. However, the hypothesis of a general sensory reweighting deficit in the elderly with a risk of falls was challenged by evidence demonstrating that no differences in postural responses were found between healthy controls and elderly fallers when exposed to wide-field visual displays oscillating with differing velocities (Allison et al. 2006).

Disambiguation of individual sensory channels and resolution of conflict between multiple available sensory channels is a central effort the postural control system is required to meet for optimal state estimation. Recently, Redfern and colleagues (Redfern et al. 2018, 2019) correlated balance performance in the SOT condition with cognitive functions, such as decision speed, control of cognitive conflict and abilities of visuospatial processing and memory. In older adults, they observed relationships between body sway in conditions with differing demands on sensory integration and specific cognitive processes. Perceptual inhibition performance correlated with sway in all conditions with a fixed support base, especially when visual feedback was sway-referenced. From this one, could deduce that processes, that resolve visual cognitive conflict, also contribute to sensory integration and intersensory conflict resolution when the control of body sway relies predominantly on somatosensory afferences and a down-weighting of vision is required. In the condition when both vision and somatosensation are reliable and equally informative, task switching performance correlated with body sway, which might suggest that similar switching between sensory channels occurred in this condition. Finally, decision speed was correlated with sway in those conditions with unreliable visual and somatosensory feedback and relative up-weighting of vestibular signals, which implies that when the postural system relies on only one sensory modality, then postural decision-making and response selection may be based on similar cognitive functions (Redfern et al. 2018, 2019). Thus, it seems that processes for cognitive conflict resolution are involved in the management of intersensory organization for balance control.

In contrast, the immediate necessity to adjust sensory reweighting following a sudden change in the environmental dynamics seems to be impaired in older adults. Jeka et al. (2010) exposed participants to an oscillatory visual environment to entrain spontaneous body sway and determined their responsiveness in terms of the visual gain. The visual oscillation would jump at some point from a low amplitude (less disturbing and requires up-weighting the visual gain) to a high amplitude (more disturbing and required down-weighting the visual gain) or vice versa. The authors found generally higher gains in older adults, which might reflect a compromised ability to reweight the visual channel and an overreliance on visual feedback. With respect to a sudden change in the reliability of the visual channel, however, they observed a slowed down-weighting in older adults with or without increased falls risk compared to younger adults (Jeka et al. 2010). This shows that older adults take longer to adapt their postural control system to a sudden environmental change. A similar conclusion was drawn by Doumas and Krampe (2010), who habituated younger and older adults to changes in the relative reliability of lower leg muscle proprioceptive feedback of body sway by sway-reference (remove sway-related proprioception) or reverse sway-referencing (augment sway-related proprioception) of the support base. Following an extended sway-referencing period and stabilization of the support, older adults demonstrated a marked and longer-lasting overshoot of body sway during proprioceptive reintegration (Doumas and Krampe 2010).

2.5 Section Summary

To summarize this subchapter, we argue against the notion that cognition as a category of high-level processes is separated from processes resembling balance control and that interference between these two entities is caused by either competition for a general resource or by the need to coordinate the activity of two subsystems of the CNS. Instead, we like to argue that cognition and balance control resemble behavioural expressions of at least two distributed brain networks that overlap in terms of structure and function within the central nervous system. This correspondence between the two domains in functional aspects means that any mutual interference when performing a cognitive and a postural task simultaneously is not a flaw in the cognitive architecture of the human brain but a central hallmark of its evolved efficiency.

The scientific evidence that we compiled in the above sections suggests that interference between certain cognitive and postural control functions occurs on several levels of the processing hierarchy. In the following, we like to discuss two alternative staging areas, the brain region encompassing the temporoparietal junction and inferior parietal lobe (TPJ/IPL) and the frontal brain region in particular the anterior cingulate cortex (ACC). The TPJ/IPL is involved as a crucial node in several parallel networks serving different functions, such as bottom-up (spatial) attention, self-perception, introspection and memory and social cognition (Igelstrom and Graziano 2017). Generally speaking, the temporoparietal junction and inferior parietal cortex is involved in information processing and perception for many different task-specific demands. The parieto-insular vestibular cortex (PIVC; Dieterich and Brandt 2019), although its name implies a role in vestibular sensation, is really a multimodal area where multiple sensory afferences carrying information about self-motion and motion of the environment converge, the distinction between self and other is made and a continuous representation of the self and its relation to the environment is kept online. The crucial aspect is that the CNS needs to infer this self-other distinction from its expectations and the afferent sensory information.

Any representations of the self and its surroundings, including egocentric frames of reference, are accessed for behaviours in the context of many spatial tasks and activities. If a cognitive stimulus in a cognitive-postural dual-task situation requires processing or mental transforming of spatial information, we can expect activity interference within the TPJ/IPL area. If certain neural assemblies are contributing to several information processing networks, then activation of one network could cause incongruent activation and interference in the other. For example, overt shifts of the focus of visual attention involving eye movements, or perhaps even covert shifts of attention, could bias the interpretation of visual and vestibular afferences for sensorimotor processing for balance control.

An important aspect is the question, what it means if one assumes an increase in automaticity of postural and balance control during cognitive-postural dual-tasking. We do not believe that the control of posture and balance can be separated into a completely parallel architecture, in which low-level modules and high-level processes can enact control independently and where the modules will take over balance control when the high-level processes are engaged in a secondary cognitive task. Instead, we believe that the control of posture and balance is continuous process like breathing that can be consciously interfered with and voluntarily suppressed but that also remains outside conscious awareness most of the time. From our point of view, balance control is an autonomous process, which will become conscious, when required by the situational demands. For example, the decision to reach for a support to stabilize ourselves following a postural disturbance happens outside our conscious awareness, and we only become aware that we have reached out to the support afterwards. It implies, however, that the postural control system has evaluated the situation beforehand and prepared a suitable response in advance potentially based on the perception of environmental affordances.

The second staging area, where we expect interference between cognition and balance control to originate from, is composed of areas of the prefrontal cortex and the ACC. The role of the ACC seems to be associated with cognitive control in a broad sense and with conflict monitoring and incongruency adaptation in particular (Shenhav et al. 2013). The functions of the ACC appear to act across domains and stimulus modalities. A central feat of multisensory integration for balance control is the detection and resolution of intersensory conflict and the upweighting of the sensory afferences with the estimated highest reliability in the context of a certain postural task. One can speculate that the ACC is involved in multisensory optimal feedback control of body balance by the provision of a cost function, which is used to maximize the expected outcome of multisensory integration but also of a planned postural adjustment. For example, the ACC has been implicated in prediction error signalling as well as event- and feedback-related negativity (Alexander and Brown 2019; Hyman et al. 2017). Thus, ACC may be involved in the detection of discrepancies between predicted and currently estimated postural states, which might require an intermittent postural correction and could be elicited by modulating planning activity in the supplementary motor area (Diwadkar et al. 2017; Takakusaki 2017). In a cognitive-postural dual-task situation, interference between the two domains may arise from the fact that conflict detection occurs in both tasks and therefore could interfere reciprocally. The effects of ageing are probably more related with ageing-related degeneration in the frontal lobes and therefore impair cognitive-postural dual-tasking performance, leading to the preference to prioritize postural control and result in difficulties to resolve multisensory conflict in an optimal fashion or in the selection of inadequate postural adjustments.

Only few papers have tried to accommodate to the known limitations of the regular sway parameters, as described in Lacour et al. (2008). More recent studies investigated the dynamics of body sway in more detail using approaches in time and frequency domains (continuous wavelet transform) or used measures of sway diffusion (stabilometry diffusion analysis, detrended fluctuation analysis) and entropy (approximate entropy, sample entropy, recurrence quantification analysis) to quantify the underlying complexity of body sway variability (Lacour et al. 2008). These more complex sway measures in future research could potentially lead to new fundamental insights concerning the interplay of specific postural control mechanisms and cognitive-postural multitasking.

3 Multitasking Involving Concurrent Timing Tasks

Timing is considered one of the key aspects of action control constraining human behaviour at perceptual as well as production levels. Predicting the duration of events and aligning this to the temporal control of one’s movements is crucial to planning, implementing and coordinating everyday activities such as speech perception and skilled performances like playing music or synchronizing one’s movements with another person during dancing. Following Gibson, time perception in the strict meaning does not exist because humans do not have a dedicated organ for the perception of time. Consequentially, related processes and experimental tasks have been labelled "duration judgement" or "duration estimation" tasks. In a typical duration judgement paradigm, participants are presented with a target duration, which they then have to reproduce, compare with other durations or bisect (i.e. indicate when half of the duration has passed). Key-dependent variables are accuracy (over- or underestimation) and the variability of estimates. When studied in multitasking contexts, duration judgement tasks are combined with concurrent tasks, for the most part working memory tasks. Duration judgement tasks have enjoyed much popularity to this end, because "time perception" does not require any overt behaviour on the part of the individual and can thus be easily paired with concurrent tasks without risks for trivial interference at peripheral input or output levels.

3.1 Models of Movement Timing

The dominant model of timing in duration judgement tasks is the pacemaker-accumulator model (Buhusi and Meck 2005) which has several classical predecessors (Creelman 1962; Treisman 1963). According to this model, timing arises from an internal clock or pacemaker which emits periodic pulses at a speed dependent on physiological parameters like body temperature or arousal. Time "perception" amounts to the registration and counting of incoming pulses by an accumulator and storage of a representation of the count in working memory where it resides for subsequent comparisons or as a template for reproduction. A critical mechanism in the model is a gating device or switch which connects pacemaker and accumulator. According to the model, this mechanism requires attention; else clock pulses are missed causing delays before the criterion number of pulses is reached. The assumption that multitasking entails interruptions in the accumulation process of temporal information matches with the common observation that "time seems to fly when you are having fun" meaning that experiences of passing time underestimate objective time when we are engaged in demanding activities.

These intuitions have been confirmed in objective experimental testing in early classical studies. For example, Hicks and colleagues (Hicks et al. 1977) had participants perform a card sorting task varying stimulus uncertainty by manipulating the number of stacks. They found that verbal estimates of the (constant) time passed decreased systematically with processing demands (uncertainty or suspense of the game). In prospective timing tasks (when participants know in advance they will have to estimate or reproduce a presented target duration), multitasking effects on time perception have differential effects during learning and reproduction (Fortin and Rousseau 1998). Participants trained with a certain target duration under single task conditions systematically underestimated time passed (i.e. produce intervals longer than the target duration) when they performed a secondary task during reproduction. The lengthening of reproductions is proportional to the time demands of the secondary task. By the same token, reproductions are systematically shortened if the secondary task was presented during learning. One exciting finding from later experiments by Fortin and Massé (2000) was that actual engagement in a concurrent task may not even be necessary to produce costs of multitasking. The authors used a break estimation procedure in which participants were asked to temporarily suspend the time perception process after an alert signal. Lengthening of produced intervals systematically increased the later in the trial the suspension signal occurred. Moreover, lengthening was the largest when the signal was never presented suggesting that anticipating the onset of a concurrent task or interruption is already creating an attentional distraction. These findings are in line with studies suggesting that the mere preparedness to multitask (e.g. by the presence of a smartphone or access to the Internet) can lower performance or the perceived quality of an interaction without anybody actually engaging in multitasking.

More recent studies suggest that multitasking might have effects beyond disrupting the accumulation of temporal information. An important aspect to consider is that interference is typically bi-directional, that is, not only duration judgements are affected by concurrent tasks, but these also show performance declines due to concurrent temporal information processing. Based on his review of 33 dual-task studies, Brown (2006) concluded that 67% observed reliable, bi-directional interference between time perception and distractor tasks. Some studies failed to find bidirectional effects of multitasking on duration judgement (Fortin and Breton 1995; Ogden et al. 2011). In what was probably the most conclusive study on the role of executive functions (cognitive control) on time perception, Brown et al. (2015) participants reproduce target durations while concurrently performing a flanker task, a number-letter task, a Go-NoGo-task or an anti-saccade task representing different inhibition facets of executive control. In all dual-task conditions, time perception was reliably impaired leading the authors to formulate the *executive resource theory of timing*, which postulates that time perception relies on specialized attentional resources that support executive functions.

Far fewer studies have used movement production tasks to assess the interference of timing with concurrent task demands. To some degree, this is probably due to the continuous motor demands inherent to such tasks which limit response formats of concurrent tasks. For example, interferences between continuous finger tapping and manual reaction time tasks trivially arise at peripheral levels. Many earlier studies used motor tasks as secondary tasks like tapping at maximum rates, and analyses were restricted to performance on the primary, cognitive tasks. Other motor multitasking studies investigated accuracy of tracking movements, and we discuss related evidence in the following section. Here we focus on studies emphasizing *explicit* movement timing, that is, participants perform periodic, discrete movements realizing prescribed target intervals. Typical paradigms introduce target tempos by providing pacing signals to which participants synchronize. Frequently, the pacing signal is discontinued in the critical test phase (continuation), and participants time their movements without external support. Dependent variables are the variability (accuracy) of produced intervals, its mean accuracy compared with the target interval and the stability (drift) in observed time series.

Traditional models of explicit timing for discrete, repetitive movements do not foresee central cognitive mechanisms or resources that would lend themselves to interference in multitasking situations. The classic two-level timing model proposed by Wing and Kristofferson (Wing and Kristofferson 1973a, b) features a central clock similar to the pacemaker described above and motor delay processes that independently contribute to central clock variability during implementation. The original model depicts movement timing as an open-loop process without error correction based on cognitive feedback processing. Multitasking studies using explicit timing tasks have been inspired by the idea of the central clock and the two-level timing model, and they also addressed a long-standing issue in the timing field: tempo or, technically speaking, the duration of target intervals. As musicians know well, playing slowly has its own specific challenges in terms of accuracy (variability). In extant timing models, this fact is reflected in assuming a systematic increase in variability as a function of interval timed and hence pronounced variability in conditions requiring longer target durations (Gibbon 1977; Wing 1980). While the exact form of the relation remains a matter of debate, empirical support for the duration-variability relation is overwhelming. Rather than attributing these findings to a single clock mechanism, several authors have argued that faster (i.e. sub-second range) and slower (i.e. > 1 s target intervals) engage different neurocognitive mechanisms. Related proposals argue for automatic, subcortical mechanisms in the sub-second range and cortical mechanisms for longer target durations (Ivry and Keele 1989; Lewis and Miall 2003; Wiener et al. 2010). Several authors argued that longer interval timing involves cognitive processes like memory or mental counting (Grondin et al. 1999; Rammsayer and Lima 1991).

Krampe and coworkers (2010) used a multitasking paradigm to address these issues. Participants tapped isochronous (one target duration) sequences with sub- (550 ms) and supra-second (2100 ms) target durations. In the dual-task conditions, they concurrently performed cognitive tasks (N-Back) differing in working memory demands. The authors observed bi-directional interference, that is, working memory performance as well as timing accuracy (mean produced interval duration, drift, variability) suffered from multitasking. In line with the assumption that timing longer intervals involves additional processes compared with sub-second timing, dual-task effects were pronounced in slow tapping conditions. Performance decrements in the timing tasks directly reflected processing demands in concurrent working memory tasks. In contrast with the bulk of findings obtained with duration judgement tasks, Krampe et al. (2010) found systematic *shortening* of produced intervals under concurrent task load. This pattern of results was reproduced and extended in a later study by Meijer and Krampe (2018). They combined sub-second interval production with two concurrent tasks that involved counting or adding visually presented digits. In the most difficult multitasking conditions, participants had to switch between the two digit-tasks while maintaining interval production. This condition produced the largest dual-task costs including interval shortening and detrimental effects on drift and variability. Detail analyses suggested that the two intervals immediately succeeding the presentation of visual stimuli from the concurrent cognitive task were the most affected in terms of timing perturbations and resulting error corrections. From these findings, the authors concluded that even sub-second timing of simple movement tasks involves cognitive control processes (Krampe et al. 2005). Similar conclusions were reached by Holm et al. (2017) who combined sub-second interval timing with concurrent finger sequencing or memory tasks.

While interval shortening due to concurrent task load is at odds with extant models of duration judgement, it is fair to say that it has been the rule rather than the exception in multitasking studies using continuous movement production tasks.

This is particularly true for studies investigating musical performance. For example, Çorlu et al. (2015) had experienced musicians perform a musical piece with and without a secondary task. Under dual-task conditions, musicians made shorter pauses between phrases, while the tempo of the phrases itself remained unaffected. Maes et al. (2015) had cellists perform melodies consisting of fixed short (700 ms) or long (1100 ms) target durations with either discrete (staccato) or continuous (legato) bowing movements. When concurrently performing a working memory task, musicians produced shorter and more irregular intervals for discrete bowing movements in the long target condition. This study is also interesting because it highlights the role of movement type (discrete vs continuous) as a factor in multitasking costs. Several authors have argued (Zelaznik et al. 2002) that continuous movements (like intermittent circle drawing) might be possible without an explicit representation of the target duration. In turn, this type of implicit timing might be less sensitive to interference.

To allow for neuroimaging during multitasking, Johannsen et al. (2013) took an innovative approach. They had participants perform auditorily paced ankle wrist movements at periods (.5 Hz) resembling normal gait. When subjects had to simultaneously work on a complex N-Back working memory task, their movements became faster, less regular and more poorly synchronized. The authors argued that this "hastening" of motor performance under dual-task conditions reflected a re-automatization of motor control. In other words, higher-level cognitive control typically involved in movement timing was impaired by concurrent task load such that automatic processes gained more influence and changed movement parameters. fMRI data indicated that these changes coincided with reduced activities in the left inferior frontal gyrus (IFG) and the superior parietal lobule.

Another group of models based on dynamic systems theory considers timing as a property *emerging* from motor processes themselves, for example, as the result of coupled oscillators presumably underlying bimanual coordination (Schöner, 2002). Different from models of *dedicated* timing, emergent timing models do not assume specific timing mechanisms like a clock that can be programmed to produce a certain target interval and provide common timing information for different limbs. Each limb combination forms its own timing system, and synchronization with external pacing is reached via entrainment. Naturally, multitasking in related paradigms does not feature central, cognitive mechanisms, but emphasizes peripheral coordination and interference like what can be observed in a person sitting passively in a chair while holding two pendula in their hands (Treffner and Turvey 1995). There have, however, been attempts to bridge representational and dynamic systems models using multitasking approaches arguing that central attentional mechanisms contribute to stability in interlimb coordination (Temprado et al. 1999). Another important contribution of dynamic system theory is that their proponents have developed data analysis and modelling techniques that do not require the assumption of stationarity. Given that most studies that investigated the dynamics in more detail actually found non-stationarity in observed time series for movement timing and postural control data, several authors proposed the use of fractal (Fourier spectrum) or non-linear measures of information complexity (e.g. Ding et al. 2002; Engbert et al. 1997).

3.2 Interindividual Differences and Age-Related Effects

Age-related differences in multitasking have been investigated with both duration judgement and movement production tasks. In duration judgement tasks, older adults have been found to show larger estimation errors than young adults (Anderson et al. 2014; Pütz et al. 2012). A meta-analysis conducted by Block et al. (2010) suggested that multitasking affected duration judgements in older and younger adults to equal degrees. Later studies conducted by Brown et al. (2015) arrived at different conclusions as they found higher multitasking costs in older compared with young adults when duration judgement tasks were paired with different executive control tasks requiring inhibitory functions. As to movement production, the aforementioned studies by Krampe et al. (2010) and Meijer and Krampe (2018) both tested young as well as older adults. The bigger picture emerging was that older adults' timing is more heavily affected by multitasking, which is reflected in pronounced interval shortening, stronger drift, increased variability, and higher susceptibility to entrainment with periodic visual stimuli. Interestingly, in multitasking contexts, older adults' slower performance (i.e. the production of longer intervals) showed larger decrements compared with fast tempos and younger adults. This pattern of results is surprising given that timing of simple, isochronous movements like those used in dual-task studies shows little if any age-related decline in healthy older adults under single-task conditions (Duchek et al. 1994; Greene and Williams 1993; Salthouse et al. 1979) even for supra-second target durations (Krampe et al. 2000, 2005). One way of reconciling these results is to assume that older adults rely on different mechanisms than young adults when doing such timing tasks even under single-task conditions. This compensatory strategy breaks down when a secondary task is added leading to higher costs. A similar interpretation was proposed as the cognitive compensation hypothesis introduced by Li and Lindenberger (2002).

3.3 Section Summary

In sum, a bulk of studies strongly suggests that timing is susceptible to interference from concurrent tasks, and this has been demonstrated for time perception as much as for movement timing tasks. The nature of the timing task plays an important role in this context. Longer intervals or sequences of different intervals increase dual-task costs. Likewise, populations with presumably limited processing resources like children, older adults or patients are more susceptible to task interference. At the same time, multitasking costs are not limited to complex tasks or special groups but can be observed in simple tasks and healthy young adults. Different from the assumptions of early timing models, task interference cannot be traced to a single component like a central clock or the attentional gate. An important contribution of multitasking studies has been to demonstrate that time perception and movement timing rely at least partly on different mechanisms, and this is equally true for timing short versus long target durations. The observed pattern of multitasking costs strongly suggests that all these mechanisms are sensitive to concurrent-task interference the degree of which however depends on cognitive capacity as determined by individuals' age. Recent findings point to the importance of the complexity of the task performed simultaneously with the timing task. Multitasking costs in timing directly reflect the concurrent tasks' demands on working memory and other cognitive control processes. Reflecting these findings theories of duration judgement (Brown 2006; Brown et al. 2015) as well as movement timing (Holm et al. 2017; Krampe et al. 2005; Meijer and Krampe 2018) have been revised to incorporate cognitive control processes.

4 Multitasking During Visuomotor Tracking

Visuomotor tracking is a prime example for the interplay of perception and action and as such part of many complex everyday activities like navigating through space and among moving objects (walking or driving), watching your opponents in team sports or tracking a continuous line on a touch screen. Different from passive viewing or romantic activities like watching the clouds, visual processing in visuomotor tracking is performed with the explicit goal of informing our actions. So conceived, it is already by itself inherently multitasking. Another important difference with the activities discussed so far is that visuomotor tracking is an activity that by its very nature involves active and deliberate allocation of attention.

The classic visuomotor tracking paradigm involves following a visually presented predictable (e.g. sinusoidal) or unpredictable (e.g. Brownian motion) signal by controlling a joystick or mouse. Another less common method used in visuomotor tracking research is force tracking. This method is comparable to the classic paradigm apart from the fact that no joystick or mouse movement is involved. Instead, a dynamometer is used as a tool to measure force application. Concurrent and target force will be displayed, and the participant should try to match them as close as possible. One last experimental setup that should be mentioned is multiple objects tracking (MOT). Here, the task goal is to memorize and track certain moving objects on a visual display. After a fixed time period, the participant will be asked to distinguish target from non-target objects. The essential difference with the tasks previously mentioned is that this task requires visual processing only.

Wickens, one of the pioneers of multitasking research, considered visuomotor tracking the perfect task for his goals because it combines processing of perceptual (nonsemantic) input with central information processing and the generation of precise motor output. In a classic paper, Wickens (1976) combined a visuomotor tracking task with an auditory task or a force application task, respectively. The auditory task involved the participant detecting and reacting to signals in noise, whereas the force application task required them to generate a constant memorized amount of force (without real-time feedback). His goal was to unravel the different processing stages in visuomotor tracking and to determine their sensitivities for dual-task interference. The auditory detection task mainly loaded on perceptual input whereas force application mostly involved output. Performance decrements due to attention-sharing multitasking were more prominent during addition of the force task than with that of the auditory detection task. From these findings, Wickens concluded that multitasking interference in tracking occurs more easily in output compared to input stages of processing.

As visuomotor tracking is an essential skill in both aviation and space travel, early multitasking tracking studies generally included these topics (Manzey et al. 1998; Manzey et al. 1995; Ververs and Wickens 1998; Wickens et al. 2003). Manzey et al. (1995) did a case study in which they investigated an astronauts' performance on four different cognitively demanding tasks before, during and after an 8-day space mission. While performance of basic cognitive functions stayed relatively stable, visuomotor tracking under both single and dual-task conditions was impaired as a result of the drastic environmental changes. Also, dual-task performance showed high correlations with subjective ratings of fatigue and emotional balance, demonstrating the importance of alertness in time-sharing activities. Manzey et al. (1998) later confirmed these results in a second study using the same participant and paradigm in a 438-day spaceflight. The authors hypothesized that early decrements in performance were mainly associated with adaptations to space environment (microgravity), whereas secondary impairments reflected stressors such as long working hours or reduced sleep quality.

Because of its high sensitivity to interference from concurrent tasks, visuomotor and visual tracking have been extensively used in training studies (Bender et al. 2017; Harris et al. 2020; Romeas et al. 2016) aiming at general benefits (far transfer) for multitasking settings. If visuomotor cognitive training improved domain-general skills beyond the actual training task, its potential for many applications like sports, aviation, military/medical training and rehabilitation would be considerable. Bender et al. (2017) trained participants on a visuomotor tracking task in combination with a discrimination perception task. The training involved 6 sessions of 36 minutes and was compared to an active control group practicing the component tasks in isolation. Results showed no transfer of improvement to action control tasks presumably sharing high-level multitasking processes with the trained tasks. More recently, Harris et al. (2020) investigated the effect of MOT training (visual training) on a visual/auditory multitasking paradigm representative of a real-world military task. The authors did find improvements in working memory performance as a result of the training. However, in line with the results of Bender et al. (2017), training did not lead to performance improvements in the real-world multitasking paradigm (far transfer). Transferability of MOT training was also researched in sports (Romeas et al. 2016). University-level soccer athletes were required to train a custom-made MOT task twice a week for 5 weeks. Control groups included active controls watching videos from the 2010 FIFA world cup™ at a frequency similar to the intervention group and passive controls who were not provided with instructions. Outcome measures were based on decision-making accuracy of dribbling, passing and shooting during recorded football matches pre- and post-training, scored by an experienced soccer coach blinded to the setup. In the intervention group, accuracy on passing but not shooting or dribbling increased significantly. Therefore, in contrast to the previously mentioned training studies, this study does provide evidence for far transfer performance improvements due to perceptual-cognitive training.

A common leisure activity, in which people constantly engage in visuomotor tracking, is video-gaming. Recently, it has been used as an accessible and cost-effective tool for training multitasking. In a study of young adults by Chiappe et al. (2013), the intervention group played action videogames for a minimum of 5 h a week for 10 weeks. When tested with a high-workload multitask paradigm that was comparable to realistic task environments, the intervention group showed better performance than controls. It seems plausible to assume that such interventions might have the largest benefits for multitasking in novices little familiar with videogames. At the same time, Donohue et al. (2012) in their study with avid action videogame players found that expert and novice players were equally susceptible to multitask-related interference. In older adults, videogame training was also implemented by using a custom-made videogame called “NeuroRacer” (Anguera et al. 2013). The game was specifically designed for multitask training and involved a joystick driving task in which participants had to keep a car centred on the road. This tracking task was combined with occasionally appearing street signs to which participants had to react only if the sign contained a green circle. The home-based training involved playing the game for 1 h a day three times a week for 4 weeks. Intervention groups included a multitasking group, a single task active control group (driving alone or the street sign detection alone) and a no training group. Results indicate the largest improvements on the task in the multitasking training group, compared to both the active control and no training. Additionally, these performance gains seem to persist for at least 6 months, as no significant decline was found during the follow-up session. More surprisingly, the training also enhanced non-task-specific abilities such as working memory and attention. Therefore, this study is the perfect evidence for supporting the robustness of cognitive plasticity, even in older age brackets.

4.1 Interindividual Differences and Age-Related Effects

Several other studies also investigated multitasking involving visuomotor tracking tasks in the context of adult ageing (Doumas and Krampe 2015; Voelcker-Rehage and Alberts 2007; Voelcker-Rehage et al. 2006). Voelcker-Rehage et al. (2006) found that working memory and force tracking both place high demands on general processing resources and that older adults require more attentional resources compared to young adults when processing such tasks concurrently. Doumas and

Krampe (2015) designed a triple-task paradigm to investigate prioritization of ecologically relevant tasks. The setup wanted to reproduce the situation of being at a party, holding a drink (force tracking) while maintaining conversation and balance. Therefore, a working memory task was combined with a visuomotor force tracking task and a postural control task. Results indicate that while both young and old adults perform worse on the visuomotor task, older adults surprisingly improved their postural stability as multitasking demands increased. This suggests that older adults tend to prioritize highly ecologically relevant tasks (postural stability) over less relevant tasks such as visuomotor tracking. From a larger perspective, these findings align to earlier results by Kramer and colleagues (Kramer et al. 1995, 1999) suggesting that the ability to differentially allocate resources remains functional in late adulthood.

4.2 Section Summary

Although original visuomotor tracking research mainly focussed on aviation and astronautics, recent tracking studies involving multitasking have been implemented in diverse fields of research. Especially training paradigms involving tracking have drawn a lot of attention, as studies have indicated domain general benefits as a result of this perceptual-cognitive exercising. Future research should be directed towards further investigating transferability of perceptual-cognitive training in large sample sizes and diverse populations.

5 Multitasking Involving Listening and Speaking

From a biological perspective, hearing is a mechanical process in which soundwaves get converted into electrical signals. This is called peripheral auditory processing. Subsequent processing at different levels can ultimately result in such complex performances as recognizing spoken language and communication. In a real-life situation, listening and speech recognition is almost always constrained by adverse conditions like being in a noisy environment or talking with multiple speakers (Mattys et al. 2012). In these situations, soundwaves of different sources overlap and enter the ear simultaneously. Despite this overlapping input, we are typically capable of detecting, identifying and separating sound sources with apparent ease. Modern theories attribute this flexibility to the involvement of several cognitive control processes. Switching is necessary to allocate/relocate the attention to the relevant speaker. Also, inhibition is needed to filter all irrelevant stimuli (e.g. the non-target speaker). These cognitive processes, particularly if operating under suboptimal listening conditions, will cause increased demands of attentional resources. Kahneman (1973) proposed the capacity model of attention. This theory assumes that people's mental capacity is limited and deliberately allocable. Therefore, performance in multitasking can stay optimal as long as task demand does not exceed the individual's capacity.

Dual-tasking involving listening and speaking has mainly been researched to gain insights into the different components of auditory processing. A key goal in this context was to assess *listening effort* and related differences between situations and individuals. This term refers to the amount of cognitive resources required for speech understanding (Downs 1982). Listening effort has been assessed via self-report or physiologic measures (e.g. heart rate variability, pupil dilatation). The dual-task paradigm offers a behavioural alternative (McGarrigle et al. 2014) in which participants perform a primary task (typically sentence or word recognition in different noise-level conditions) concurrently with some secondary tasks like visual tracking, reaction time, word recall or tactile pattern detection. Listening effort is defined as the difference between secondary task performance in isolation and that under dual-task conditions. This definition is based on the assumptions of the aforementioned capacity model of attention (Kahneman 1973). According to this theory, the increased resources needed to successfully execute the prioritized task in dual task conditions will directly influence the secondary task performance. Gagne et al. (2017) reviewed dual-task studies targeting listening effort in adults. The authors found that in general, both age and hearing loss increased the amount of listening effort expanded for a given task. In contrast, the effects of cognitive abilities (e.g. working memory capacity) and perceptual modality (visual vs audio-visual) on listening effort remain inconclusive.

Listening and speaking in driving is a naturally frequently occurring situation, and multiple studies have been conducted on this topic (Bergen et al. 2013; de Waard et al. 2010; Kubose et al. 2006; Lee et al. 2017; Strayer and Johnston 2001). In these studies, real-world or simulated driving was combined with active listening and/or talking. In general, both listening and talking influenced driving performance negatively (e.g. traffic signal detection, reaction times). Also, talking seems to induce more performance decrements compared to listening (Lee et al., 2017), and talking about motor or visually related topics seem to cause additional interference compared to having an abstract conversation (Bergen et al. 2013). These results suggest some degree of higher-level cognitive interference in listening and speaking multitasking. On the other hand, de Waard et al. (2010) investigated low-level passive listening. Participants had to cycle on a bike path during certain conditions, including calling, texting, listening to music and two control conditions. Results show that, in contrast to calling and texting, music listening had very limited effects on the concurrent cycling.

Although the solid body of evidence involves multitasking, listening and speaking, multiple limitations need to be mentioned. In the listening effort studies, three essential problems arise. First, the assumption that all available resources are used during task performance cannot be verified. Also, primary task prioritization is a necessity for clear interpretation of behavioural listening effort. Additionally, greater secondary dual-task costs are interpreted as increased listening effort, although multiple other explanations for performance decrement in dual-task conditions can be suggested. For example, the performance decrement could be related to an increased amount of switching and inhibition costs needed in the dual-task condition, irrespective of listening effort itself (Seeman and Sims 2015). In studies focussing on ecological relevance, the most important limitation lies in the inherent goal itself. While these studies are seemingly able to represent aspects of daily living, they are still lab-based setups with somewhat artificial instructions.

5.1 Interindividual Differences and Age-Related Effects

Individual differences in listening and speaking multitasking have been studied in a wide variety of populations and experimental setups. In children, Choi et al. (2008) set up an experiment in which participants had to combine a listening task with a working memory digit recall task. Children from age 7 to 14 were included and divided into two groups. One group was asked to prioritize the listening task, whereas the other group had to focus on the digit recall task. Despite these prioritization instructions, both groups showed performance decrements under dual-task conditions in the digit recall but not in the listening task. Therefore, the authors suggested that top-down cognitive control and resource allocation are not fully developed at least until the age of 14. Later studies in children by Howard et al. (2010) and Picou et al. (2019) used a more naturalistic approach, as they investigated the effects of a typical classroom setting on speech recognition and listening effort. Howard et al. (2010) used an experimental setup similar to Choi et al. (2008) by combining listening word recognition with a digit recall task. The investigators manipulated the difficulty of the listening task so that they could compare performance in a quiet room to different classroom noise levels. Although results on the listening task did not decrease in dual-task setting, participants performed significantly worse on the digit recall task in higher classroom noise levels. Picou et al. (2019) recently supported these findings using a similar listening in noise task, combined with a visual probe secondary task. Typical classroom noise could lead to increased listening effort, leaving less attentional resources available for other potential tasks.

In ageing adults, Lundin-Olsson et al. (1997) noticed how frail elderly have the tendency to stop walking when they are expected to conversate while walking. Therefore, they set up an experiment to see how well this indicator could predict future falls. In their case study, they demonstrated how this easy to assess measurement is able to predict falls with a positive predictive value of 83% and a negative predicting value of 76%. Since then, multiple authors have confirmed the predictability of falls using a “walking while talking” (WWT) assessment (Ayers et al. 2014; Bootsma-van der Wiel et al. 2003; Muhaidat et al. 2014; Verghese et al. 2002). Ceide et al. (2018) recently found that WWT gait parameters could also be used to determining the risk of developing dementia in older adults. Raffegeau et al. (2018) on the other hand investigated WWT in young healthy adults to see how different situations (difficulty manipulation) could influence resource allocation in WWT (Raffegeau et al. 2018). The authors demonstrated that even young adults require significant cognitive resources for this habitual multitasking activity. Additionally, they concluded that young adults are able to flexibly allocate resources between tasks according to their difficulty. In extension of the standard WWT protocol, Krampe et al. (2011) researched the interaction between walking and a high-level cognitive speaking task across lifespan. Participants were instructed to walk on a narrow track while concurrently summing up words of a semantic category. No prioritization instructions were given, meaning both tasks had to be performed optimally. Results indicate a U-shaped relation between age and dual-task costs in walking, in which both children and old adults show higher dual-task costs compared to younger adults. The semantic speaking task was mostly unaffected by concurrent walking, with only one group of children performing significantly worse in dual-task conditions. As the walking task was considered not threatening to any age group, the prioritization of the high-level cognitive talking task highlights the ability of people to accommodate to the current taskset, including children and older adults.

5.2 *Ecological Aspects of Listening and Speaking*

Recently, several research groups have tried to develop paradigms emphasizing listening and speaking under multimodal demands of daily living. The StreetLab is an excellent example of these more naturalistic designs. It involves an immersive virtual reality laboratory designed to mimic crossing a street. Lau et al. (2016) and Nieborowska et al. (2019) used this setup to combine this street crossing task with a listening in noise word recognition task. Lau et al. (2016) demonstrated that old adults generally prioritized walking over the listening task, with this pattern being independent of task difficulty in individuals with hearing impairment. Nieborowska et al. (2019) later supported these results as they compared younger to older adults. Here, older adults showed improvements in walking performance with increasing task difficulty whereas younger adults did not. These findings also corroborate with Bruce et al. (2019) who found that young but not older adults showed performance decrements in dual-task postural control when balance and listening were combined. In conclusion, these articles all support the “posture first” hypothesis in old adults which implies the allocation of cognitive resources towards fall risk reduction at the cost of concurrent task performance. In 2020, Devesse and colleagues studied multitasking with the goal of investigating a real-life complex listening condition (Devesse, van Wieringen, et al. 2020; Devesse, Wouters, et al. 2020). The paradigm was called AVATAR (Audiovisual True-to-Life Assessment of Auditory Rehabilitation). Tasks were presented in a virtual restaurant scenario and involved listening to virtual humans, concurrently combined with up to three tasks. The results indicate that while both young and middle-aged adults have a stable primary task performance across conditions, performance of the secondary tasks decreased as more tasks were concurrently combined. The authors concluded that with increasing task complexity, listeners need to allocate more cognitive resources to achieve the same level of listening performance. Additionally, performance decrements were significantly larger for middle-aged compared to young adults in triple and quadruple conditions, suggesting middle agers experience greater performance decrements due to multitasking when listening is involved. With rising interest in recreating real-life situations combined with the implementation of these paradigms in virtual reality, many research opportunities arise. These multimodal though controllable settings could broaden our knowledge on everyday problems of people with hearing loss as well as facilitate hearing rehabilitation transferability (Campos et al. 2018).

5.3 Section Summary

In summary, multitasking involving listening and speaking has been researched in a variety of topics. Recently, ecologically relevant studies have gained popularity with the development of the StreetLab and AVATAR. Although sometimes perceived as effortless, listening or speaking in a multitasking scenario will most likely result in performance decrements. The extent to which these decrements occur is dependent on individual differences such as age and hearing loss. Also, the number of adverse conditions and cognitive involvement seems to be an essential influential factor, highlighting the importance of domain-general interference in listening and speaking multitasking.

6 General Summary and Discussion

In this chapter of the handbook, we have described research into four multitasking situations, in which cognitive or motor performance relies on continuous sensorimotor processing and action control. This final section will discuss the explanatory reach of popular theories regarding cognitive-motor interference in continuous multitasking. From this discussion, we will derive and delineate a suitable theoretical framework for the understanding of multitasking interference in continuous tasks with and without production of action or movements. We assume that in these situations, variable autonomy with respect to demanding cognitive control is demonstrated made possible by the possibility to utilize several control processes in parallel.

Neither the single capacity sharing theory nor the single bottleneck theory appears to be suitable explanatory frameworks for an explanation of the diversity of multitasking interference in continuous tasks. The primary conundrum regarding many continuous sensorimotor tasks is that they appear less effortful and are rated as subjectively less resource demanding than discrete tasks, for example, continuous adjusting compared to discrete adjusting (McCracken and Aldrich 1984). Thus, as a distinction between separate task stages is generally harder, resource and capacity sharing theories appear to not to apply well to the field of continuous cognitive and motor behaviours. Stimulus-processing, selection and execution in continuous multitasking activities are experimentally not as clearly controlled and may occur only occasionally in contrast to discrete cognitive multitasking situations. Unfortunately, theoretical accounts are often favoured in the literature that propose general attentional capacity allocation to limit performance during continuous multitasking situations. The fundamental under-specification of general resource sharing accounts prevents, however, the prediction of specific interference effects in continuous multitasking situations.

Another crucial aspect that is different in continuous multitasking situations is also that in traditional discrete cognitive dual-tasking situations, the selection of responses for either of the interfering tasks is mostly considered a conscious process of deliberate decision-making as well as the stage of processing from where any task interference originates. Following this line of thinking, it seems straight forward to argue that in cognitive-motor dual-tasking, movement execution is more automatic when the competing cognitive task is prioritized in terms of the attentional focus. What is not clear, however, is what it entails, when a movement is claimed to be more automatic than consciously controlled and whether this makes a difference in the nature of the task. It seems that a continuous nature is considered the decisive quality, which results in continuous tasks being interpreted as "automatically" controlled.

Thus, the notion that movement control in a cognitive-motor multitasking situation is automatic may be actually caused by a certain degree of parallelism in control processes. In order to explain variable time-sharing performance in multitasking situations, Wickens and colleagues' (Wickens 2008) multiple resource model allows for parallelism during the execution of multiple tasks depending on the overlap of concurrent tasks onto four multi-levelled dimensions: processing stage, perceptual modality, visual channel and processing code. Interference would occur between two tasks, if they overlapped on one specific level of a certain dimension.

The theory of hierarchical control of cognitive processes by Logan and Crump (2011) assumes two nested feedback loops, an outer and an inner feedback loop, that are engaged following an action. Each feedback loop compares whether the current state of a system meets a predefined goal state. If current and goal states differ, then an operation is executed, which is expected to reduce the difference between the two states. Subsequent to this operation, another comparison between states is conducted, and if a match has been achieved, then the next action is performed. While the outer loop is concerned with more abstract goal conceptualizations, the inner loop is engaged by concrete muscle activation and control of movements. Both loops are hypothesized to act on qualitatively different feedback channels. The outer loop provides input to the inner loop, but has no access to the activity of the inner loop, which is informationally encapsulated (Fodor 1983; Logan and Crump 2011). Medeiros-Ward et al. (2014) applied the hierarchical control theory to a continuous task such as driving a car and concluded that attentional resources are required by the outer loop, while the inner loop shows performance degradations when attention is focussed on its activity. This pattern resembles observations in human postural multitasking explained by the so-called "constrained action" hypothesis, which assumes disrupted postural performance when voluntary control of sway is imposed (Wulf et al. 2001, 2003).

Regarding multitasking in continuous tasks, we see it as more fitting to postulate different levels of "autonomy" of action control, instead of "automaticity", associated with differing levels of adaptability to changes in the task context. Thus, an important aspect regarding the allocation of processing resources is that it occurs in an adaptive manner, which is influenced by the specificities of an individual's goals, the demands of the tasks to be performed and the situational and environmental constraints. For example, Fischer and Plessow (2015) argued that efficient multitasking implies adaptation of multitasking performance to situational and environmental demands, so that shifting between more parallel or more serial task processing strategies depends on specific task-relevant conditions. Similarly, taking a lifespan developmental perspective, Baltes and colleagues (Freund and Baltes 1998, 2002; Krampe and Baltes 2003) suggested the selection, optimization and compensation (SOC) metatheoretical concept. According to the SOC model, an individual adapts strategically and tactically to the challenges imposed by a given (multi-)task situation by selecting a more narrowed focus on specific goals and functional results, by optimizing functional outcomes through targeted resource allocation and by developing and adopting compensatory strategies and techniques.

The tasks and activities that we described in this chapter are characterized by the feature that task execution does not require discrete conscious decision-making efforts with the exception of those instances when salient events in the specific action context occur. For example, a detected deviation from a predefined performance criterion might require more cognitively controlled evaluative processes to adjust behaviour. These decision-making processes, however, do not need to be conscious in terms of focussed attention onto specific features of a discrete external stimulus as it has been often demonstrated that the execution phase of goal-directed behaviours, such as saccades or manual reaching movements, is under the control of an "autopilot". This "autopilot" is capable of responding to sudden displacement of the location of a behavioural target by automatic online movement corrections that do not require voluntary intervention (Desmurget et al. 1999; Desmurget and Grafton 2000; Gaveau et al. 2014; Gomi 2008; Pisella et al. 2000; Potocanac and Duysens 2017; Prablanc et al. 2003). It has been suggested that neural networks within the posterior parietal cortex are involved in the automatic error processing underlying the flexibility in during movement execution (Archambault et al. 2009; Pisella et al. 2000).

Desmurget and Grafton (2000) suggested that an internal forward model is continuously updated by sensory afferences during execution of movements such as arm reaching to generate and estimate of the most likely current position and velocity of the effector. Subsequently, any discrepancy between the estimated position and the initially predicted position is supposed to result in an error signal that is used to correct an ongoing movement. Rodriguez-Fornells et al. (2002) suggested that error-related negativity reflects the response of an evaluative system engaged in the monitoring of motor conflict. They proposed that a predictive mechanism, which compares an efference copy of a motor command to a predicted accurate response and which tries to inhibit an incorrect response or executes a corrective action if the inhibition fails.

Research into the timing of actions has considered the continuous and discrete timing, such as oscillatory movements and tapping. While discrete timing is intrinsically intermittent with respect to timing corrections, it may be reasonable to assume similar mechanisms to regulate timing in continuous tasks as well. By using the methodology of timing perturbations, Elliott et al. (2009) showed that smooth continuous force production in response to an auditory stimulus causes temporal variability to increase compared to discrete timed force production. They concluded that action synchronization with timing events in continuous tasks is more demanding than synchronization of discrete actions. Possibly in continuous timing actions, a timing conflict monitoring process may be engaged in ongoing movement control and thus needs longer to perform a subsequent correction following a major timing perturbation due to a refractory period following a “micro-adjustment”. More frequent adjustments would result in more frequent refractory periods and thus timing delays and increased variability. In contrast, in discrete timing activities, reduced demand in online conflict monitoring and correction would evoke fewer refractory periods.

In continuous motor tasks, such as visuomotor or force tracking, intermittent discontinuities with variable timing intervals have been reported that do not represent artefacts of some other kind (Miall 1996; Miall et al. 1986, 1993; Wolpert et al. 1992). Miall et al. (1993) proposed that these intermittent discontinuities resulted from periods, during which no positional error signal was available due to a refractory period between successive corrective movements. These observations led to the action monitoring framework being applied to continuous motor tasks such as visuomotor tracking, which received considerable interest to investigate the intermittency of movement corrections in the recent decade. For example, Pereira et al. (2017) investigated event-related potentials time-locked to periodic submovements in a visuomotor tracking task and postulated that the submovements expressed activity of a low-frequency oscillatory action monitoring network involving the supplementary motor area of the human brain. Sakaguchi et al. (2015) argued that submovement intermittency in continuous tracking tasks is best modelled as an intermittent feed-forward control process with adaptive segmentation that predictively divides time into discrete segments and exerts feed-forward control in each segment. More frequent updates of the state of a movement would increase computational costs of motor planning so the control system needs to weigh a trade-off between computational costs and movement error based on incorrect predictions (Sakaguchi et al. 2015). In order to explain intermittency of corrections observed in continuous force tracking, Susilaradeya et al. (2019) used manipulations such as temporal delays of visual feedback and spatial displacements of the force indicator and concluded that interference between delays and noise in the sensory feedback loop and noisy motor commands result in discrete corrections occurring up to three times per second. Further, they argued that the intrinsic rhythmicity of cortical networks of the motor system has to be considered as the basis of an internal model of external dynamics used for state estimation during feedback-guided movements (Susilaradeya et al. 2019).

Interference between cognition and concurrent motor performance may be due to action monitoring and refractory periods in behavioural adjustments. Gawthrop et al. (2020) described a model of intermittent control of movements and balance that assumes a process of refractory response planning to occur, which uses current state estimates to prepare muscle activations that are executed without any sensory feedback. This response planer is supposedly associated with the basal ganglia and centres of cognitive decision-making in the frontal lobes (Gawthrop et al. 2020). An alternative framework for intermittent control of sensorimotor behaviour, that does not assume refractory periods or error thresholds, was proposed by Markkula et al. (2018). By modelling control of ground vehicle steering, they suggested that intermittency results from an evidence accumulation process that aims to minimize sensory prediction errors and consequently leads to refractory intervals and apparent error thresholds. Taking sensorimotor intermittency into account and relating it to cognitive-motor dual-task situations, one may therefore argue that engagement in a cognitive task may directly affect refractoriness of sensorimotor control.

Error correction mechanisms involving the ACC have been considered to depend on conscious error detection. In contrast, error detection in the domain of continuous activities does not need to become conscious and are often corrected for automatically. Does this mean that error correction mechanisms represented in the anterior cingulate cortex cannot be involved in continuous activities? According to the dual-route model of conscious versus non-conscious evidence accumulation in error detection by Del Cul et al. (2009), Charles et al. (2013, 2014) suggested that a conscious representation of a desired action is required to detect an error explicitly. According to the model by Del Cul et al. (2009), a signal that an intended action was erroneously performed is generated when the output of the faster unconscious sensorimotor route and the slower conscious route of evidence accumulation are in conflict.

The observation of ageing-related decrements in multitasking performance provides some superficial plausibility to the general resource competition account in the sense that it explains why older adults are prone to showing more severe interference effects during multitasking than younger individuals. The basic assumption is that older adults show ageing-related neural degeneration, which leads to scarcity of cognitive resources, undersupply to certain cognitive processes and therefore performance reduction in single or multiple ongoing tasks. As a consequence, older adults would need to prioritize resource allocation to those tasks and processes, where the outcome is considered of higher value to the individual and the organism as a whole, for example, in terms of avoiding physical injury. Ageing-related changes in the structure and function of the human brain differ in their rate between areas and regions, which implies that loss of cognitive resources due to ageing does not represent a general process resource reduction but may be more task- and process-specific in nature and may be related to diminished parallelism in processes involved in cognitive and movement control.

Further research is necessary with more targeted experimental designs to disentangle interference between cognitive and movement control in continuous activities. It might be especially useful to investigate intermittency and refractoriness during the production of continuous movements from a cognitive science perspective. An important endeavour will be the detection of single motor control events and the observation of how these are influenced by concurrent cognitive control interventions but also by task- and context-related factors. This may also open up new avenues of research into the effects of ageing on multitasking interference.

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Part II
Sequential Multitasking

Task Switching: Cognitive Control in Sequential Multitasking

Iring Koch and Andrea Kiesel

1 Introduction

In daily life, we are usually confronted with a variety of tasks, starting with getting up in the morning. In most cases, there is a smooth sequence of actions (picking up the toothbrush) and tasks (brushing the teeth). Similarly, when arriving at the office, you start your computer and begin responding to your emails. However, when you are interrupted by some distraction (e.g., noise on the street) or by an intervening task (respond to a phone call), you might fail to respond to a particular email and start working on a different email instead. This example shows that coordinating tasks can come with a performance costs, particularly if task order is not under control and if there are tight temporal constraints (e.g., tasks requiring swift actions). Such situations can be said to require "multitasking." Multitasking can produce harmless distraction in some cases, such as producing a lapse when not responding to an email (e.g., Reason 1990), but failing to perform a task properly or in the right time might also result in a safety-critical incident (e.g., failing to indicate a lane change during car driving in dense traffic) or even an accident. The effects and underlying psychological processes of such multitasking have been examined in

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applied contexts, such as in task interruptions in emergency wards of hospitals or in traffic, and this research is covered extensively elsewhere (see Hirsch et al. Chap. 4, this volume; Strayer et al. Chap. 10, this volume).

In the present chapter, we review empirical findings and theoretical accounts in more controlled experimental settings. We focus on the situation in which different tasks need to be performed sequentially and that requires switching back and forth between tasks. This situation has been shown to result in impaired performance during a task switch relative to repeating a task, and these performance costs have been termed "switch costs" (for reviews see Kiesel et al. 2010; Koch et al. 2018; Monsell 2003; Vandierendonck et al. 2010). From a theoretical point of view, investigating task switching abilities and limitations is relevant because this sheds light on the human flexibility to adapt behavior depending on own goals and/or depending on changing external requirements. Before we describe the basic experimental methodology, the so-called task-switching paradigm, to assess task switch costs, we first attempt to define the term "task" itself and demarcate sequential multitasking from other forms of multitasking.

A task represents a defined cognitive-motor requirement that is governed by the intention to achieve a task goal. In cognitive psychology, it has been argued that such task requirements are represented as a "mental task set" (see, e.g., Allport et al. 1994; Gibson 1941; Rogers and Monsell 1995; Spector and Biederman 1976) that implements the control processes that enable the actor to act according to the task, which implies guidance of attention to relevant stimuli, performing the correct mental operation on the stimulus representation and "translating" the outcome of this mental operation into an overt motor action. For example, categorizing a visually presented letter as a consonant vs. vowel with pressing either a left vs. right response key with the dominant hand is a task that includes a task goal (categorization), a defined stimulus set (e.g., letters from the alphabet), a set of possible responses, and a stimulus-response (S-R) mapping or a category-response mapping (if there are several letters in the category of vowels). That is, a task requires a specified motor action that is governed by a task goal (i.e., a specific intention to perform the task). This is an example of a "single-step" task that is completed with a single action (Monsell 1996). Note, however, that the same stimulus set (here: letters) can afford different tasks, such as judging whether a letter is early or late in the alphabet instead of vowel vs. consonant categorization.

The definition of a task becomes more troubling when we turn to multistep tasks, such as driving to work. There are multiple actions, or sub-tasks, in specified sequence, such as opening the car door, starting the engine, etc., that are all nested within the overall task. This example shows that it is hard to distinguish, terminologically, between actions and tasks because this simply depends on the point of view (see Künzell et al. 2018). For definitional purposes, we can say that a task requires a specified selection of an action that serves the task goal. With this definition in mind, we can now specify the term "multitasking" as a situation in which the actor has to coordinate two different task goals and thus has to maintain two different task sets. In empirical research, we can translate this into an "operational" definition by specifying how we measure multitasking effects in human performance.

A basic distinction in multitasking is whether the situation requires performing two tasks simultaneously or sequentially. Simultaneous multitasking corresponds to the classic "dual-task" situation, in which two tasks are required at the same time, and performance in each task in the dual-task condition is compared with that in a corresponding single-task condition (see Johannsen et al. Chap. 2, this volume). This comparison typically yields dual-task costs (see Fig. 1). However, because tasks are rarely performed at exactly the same time, meaning in the very same millisecond, a different approach to dual-task research is to manipulate the temporal overlap of the tasks by presenting the stimuli either with very short stimulus-onset asynchrony (SOA), which is the high temporal overlap condition, or with longer SOA, reducing the temporal overlap. The comparison of performance with short

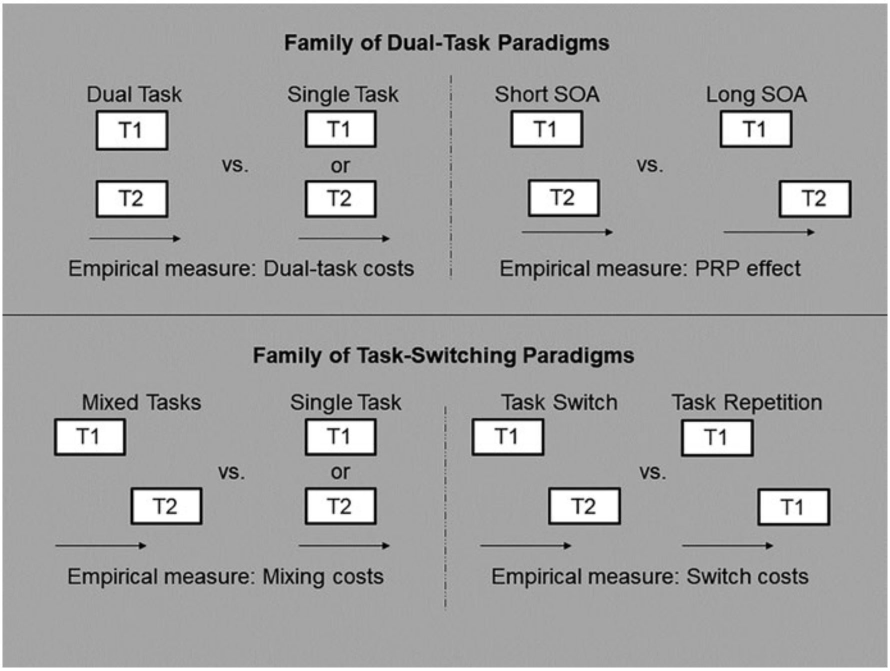

Fig. 1 Sketch of different multitasking paradigms. Upper row: In dual-task paradigms, participants perform two tasks (T1 and T2) simultaneously, and performance is compared to single-task performance (left panel) or performance is compared for simultaneous task performance (short SOA = stimulus onset asynchrony) or with increasing SOAs between tasks (right panel), resulting in a PRP (psychological refractory period) effect (see Chap. 1 of Fischer and Janczyk in this issue). Lower row: In task switching studies, participants perform one task at a time, and tasks can repeat or switch in consecutive trials. Performance is compared in mixed-task blocks and single-task blocks, resulting in so-called mixing costs (left panel; please note that there is no uniform definition of mixing costs – some studies compare performance of all trials in mixed-task blocks with performance in single-task blocks, while other studies consider only performance of task repetition trials in mixed-task blocks for this comparison with single-task performance) or performance is compared between task-switch trials and task repetition trial, resulting in (local) switch costs (right panel). (Figure is adapted from Koch et al. 2018)

SOA and long SOA gives a different measure of dual-task costs, typically showing worse performance with shorter SOA (the so-called “psychological refractory period” [PRP] effect; see Fischer and Janczyk, Chap. 1, this volume; Koch, Poljac, et al. 2018, for a recent review).

While the PRP paradigm manipulates the SOA, typically there are still conditions in which the SOA is too short to complete the response in Task 1 before the stimulus for Task 2 is presented, so that it still represents a “simultaneous” condition. However, in situations with very long SOA, tasks are performed without overt overlap and thus strictly sequentially, so that this required discrete switches of the tasks. One possible instantiation of such sequential multitasking is the situation in which an ongoing task is interrupted by a shift to a different task at some point and needs to be resumed later. This “task interruption” research is covered in a different chapter in this handbook (Hirsch et al. Chap. 4, this volume). In the present chapter, we focus on sequential multitasking as examined in the task-switching paradigm, in which two single-step tasks with more or less equal priority are performed sequentially (see Kiesel et al. 2010; Monsell 2003; Vandierendonck et al. 2010, for reviews).

In task switching, the basic phenomenon is that performance is typically impaired in task-switching conditions relative to single-task conditions. This so-called switch cost has attracted much attention in recent decades because it may reflect the operation of cognitive (or “executive”) control processes and that the task-switching paradigm could be a methodological tool to examine executive functions such as the *shifting* of mental task sets, the *updating* of S-R rules in working memory, and the *inhibition* of competing task sets or actions (see Miyake and Friedman 2012, for an approach to assessing executive functions). In turn, task switching has become a major research paradigm in experimental psychology and cognitive neuroscience.

In the present chapter, we review the research on task switching with an emphasis on behavioral findings and cognitive theories. Readers interested more specifically in the neuroscience research on cognitive control in task switching are referred to the chapter by Brass and De Baene (Chap. 7, this volume). In the following, we first describe the basic paradigm and its popular variants. Then we focus on the issue of proactive control in terms of the influence of preparation for a task switch. This is followed by a summary of research on interference effects in task switching that occur independent of (or even despite of) task preparation. Based on this empirical evidence, we summarize major theoretical accounts of task switching. We end with a consideration of interindividual differences, with a focus on gender-related differences, followed by an outlook on future research perspectives.

2 Task Switching: Basic Paradigms

In task-switching studies, in each single trial, participants perform only one task, yet the tasks switch in consecutive trials. In order to implement these task switches, several paradigms have been applied: alternating (i.e., predictable) task switching, cued task switching, and voluntary task switching. A literature research on Web of Science (on June 25, 2021) revealed that the cued task switching paradigm has been applied much more often than the two other forms of task switching. The search term task switch* or task shift* (in the databases of neurosciences or psychology or experimental psychology) combined with cue has most hits (2236), while the combination of either alternating or predictable (430 hits) and voluntary (510) was less frequent. In the following, we explain these three versions of the task-switching paradigm in more detail. A fourth form of task switching is task interruptions. This type of task switching is considered in a separate chapter (see Hirsch et al. Chap. 4, this volume) because it is less often used in basic research and more often in applied settings and because the research tradition for task interruptions differs from those for task switching, so that it is better covered separately.

2.1 Predictable Task Switching

Task switches can be implemented in a predictable manner by alternating the task sequences. The first studies on task switching instructed strictly alternating task sequences (ABAB, etc.), and compared performance in these heterogeneous (mixed-task) blocks with performance in homogenous (single-task) blocks (e.g., Allport et al. 1994; Jersild 1927; Spector and Biederman 1976). These switch costs have been referred to as general or global switch costs (e.g., Kray and Lindenberger 2000) indicating that mixed-task and single-task blocks do not only differ regarding the task-switching requirement itself but also in terms of working memory load because two tasks and thus more S-R rules have to be remembered in mixed-task blocks than in single-task blocks (Fig. 2).

To obtain a more fine-grained measure of switch costs in task switching while equating working memory load, Rogers and Monsell (1995) proposed the alternating runs paradigm, employing predictable AABBAABB task sequences (alternating runs of two tasks). Participants were instructed to categorize either a letter as vowel or consonant or a digit as odd or even by pressing the same response keys for both tasks (i.e., with overlapping S-R mappings). Stimuli were presented in one cell of a 2x2 grid and the stimulus location in the grid rotated blockwise. Hence, in addition to the predictability of the tasks, the location in the grid indicated the required task, for example, presentation in one of the two left cells instructed the letter task and presentation in one of the two right cells the digit task.

To assess switch costs in the alternating-runs paradigm, performance is compared in task switch and task repetition trials. The performance decrement for this trialwise comparison of switch and repetition trials is often considered as “local” switch costs (in contrast to global switch costs, see Meiran et al. 2000) because only the current (local) requirement differs for both conditions, while the global affordance to remember two tasks for this block remains the same. Note that the term

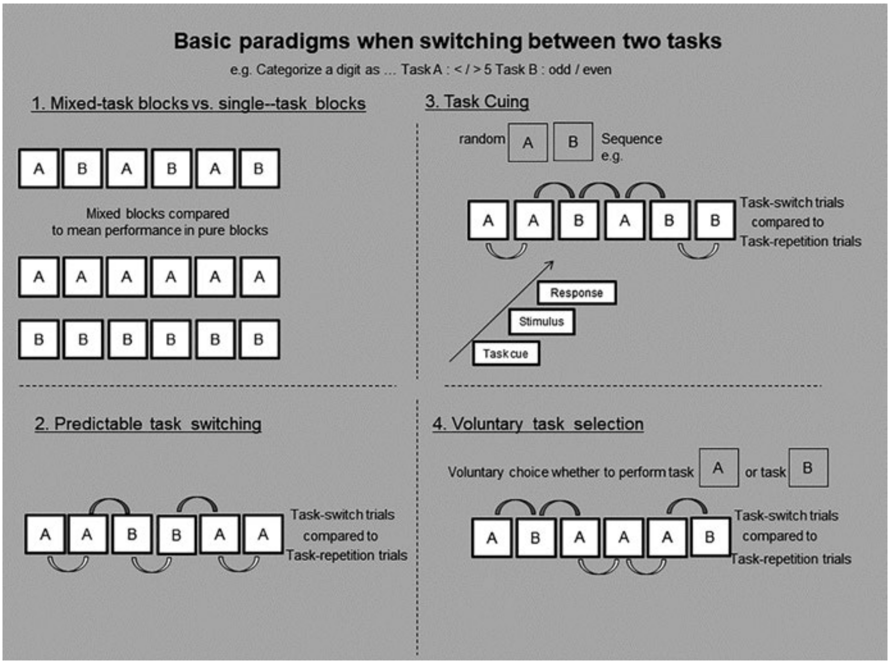

Fig. 2 Overview over basic task switching paradigms. 1. Performance in mixed-task blocks is compared to performance in single task blocks assessing mixing costs (e.g., Jersild 1927). 2. to 4. Performance in task-switch trials is compared to performance in task repetition trials assessing (local) switch costs. The currently relevant task is instructed either due to a predictable task order (e.g., AABBAA; see 2., e.g., Rogers and Monsell 1995) or by a task cue (3., e.g., Meiran 1996). In this latter case, task order is usually random. In 4. Participants themselves choose which task to perform in a given trial. To induce task switches, they are often instructed to choose tasks randomly in each trial (e.g., Arrington and Logan 2004)

"global" switch cost refers to the comparison of single-task blocks and mixed-task blocks, and these global switch costs can be divided into local costs (switch vs. repetition in mixed-task blocks) and mixing costs (repetition in mixed-task blocks vs. single-task blocks); see Fig. 3.

Variants of the predictable task-switching paradigm implemented settings with longer task runs (e.g., 4 or 8 runs/repetitions before a switch; Altmann 2014) or with task sequences that were predictable because of their fixed task sequence that is repeated several times (e.g., Gotler et al. 2003; Koch 2001, 2005; Koch et al. 2006). These studies indicated that participants' performance does not only differ in switch trials compared to repeat trials but that task predictability impacts on performance over several trials. For example, Altmann and Gray (2008) reported that when switching after each 8th trial, response times decrease in the first repetition trial and then increase with increasing number of repetitions in the run.

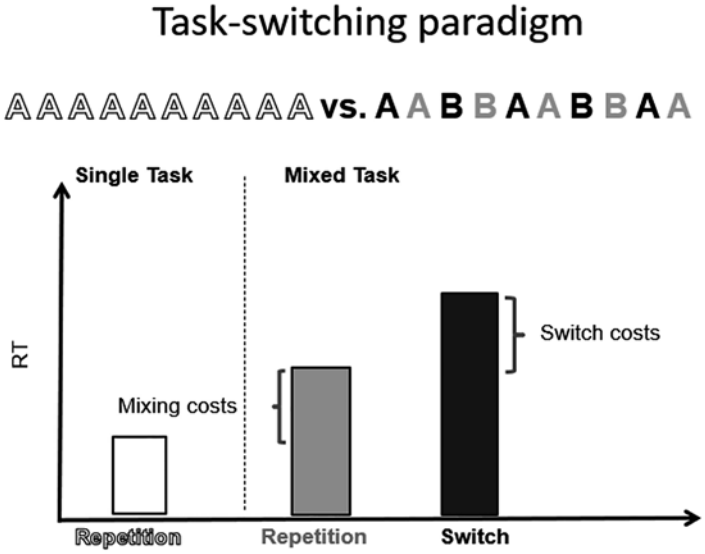

Fig. 3 Comparing performance in single-task and mixed-task blocks enables researchers to assess mixing costs, operationalized as RT (and error rates) difference in mixed tasks (often repetition trials only) and single-task blocks, as well as (local) switch costs, operationalized as RT (and error rates) difference in task-switch and task repetition trials in mixed blocks

2.2 Cued Task Switching

In the cued task switching paradigm, participants are instructed by an explicit task cue, which is presented prior to each stimulus, about the task to perform on the next target stimulus. For example, Meiran (1996) designed a paradigm in which a stimulus was presented in a 2x2 grid. Participants were asked to respond to the location of the stimulus either in terms of its horizontal orientation (left – right) or its vertical orientation (upper – lower location). To indicate which task is required in the trial, small arrows pointing to the left and right or pointing upward and downward were presented as task cues. Unlike in the predictable switching paradigm, using explicit task cues makes it possible to use a random task sequence in the cued task switching paradigm. Like in the predictable switching paradigm, local switch costs are assessed by comparing performance in switch trials with that in repetition trials (see Altmann 2007, for a comparison of both methods to assess switch costs).

A major manipulation in the cued task switching paradigm is the cue-to-stimulus interval (CSI) during which participants can prepare the upcoming task (see Koch 2001; Meiran 2000; Meiran et al. 2000; see Jost et al. 2013, for a review of cue processing in task switching). Additionally, also the type of task cue has an impact on the size of switch costs. Task cues can be meaningful for a task, for example, Sudevan and Taylor (1987) used the letters OD/EV and LO/HI to instruct participants to categorize digits as odd/even or as smaller/larger than five (low/high). Or task cues can be arbitrarily assigned to a task, for example, a square or a diamond instructing participants to categorize a digit as odd/even or as smaller/larger 5 (e.g., Kiesel et al. 2007; Koch 2003). For arbitrary task cues that have no relation to the task, switch costs are larger than for task cues that have a relation to the task and eventually directly instruct the stimulus-response mapping for each task (Gade and Koch 2014; Miyake et al. 2004). This might be taken as evidence that working memory load is increased if task cues are arbitrarily rather than meaningfully mapped to tasks and that local switch costs vary depending on WM load (see Gade and Koch 2014). Alternatively, or perhaps complementary to this account, the differences of cue types might be seen as evidence for different types of task implementations, whereby meaningful cues induce verbal task-set representations that are more robust against interference effects (Gade and Steinhauser 2020).

2.3 Voluntary Task Switching

Switch cost in predictable and cued task switching turned out to be a robust finding. Even if participants had ample time to prepare for a switch, switch costs remained ("residual" costs, Rogers and Monsell 1995; see also Kiesel et al. 2010, for a comprehensive discussion). However, one might wonder whether switching is less costly if participants themselves could decide which task to perform in each trial. In order to assess such "voluntary" task switching, Arrington and Logan (2004) instructed participants to categorize a digit either as smaller/larger than 5 or as odd/even. Thereby, participants were free to choose which task to perform in each trial. Despite the voluntary choice of task to perform, participants still responded more slowly in switch trials than in repetition trials. Nevertheless, it seems that voluntary task choice is easier because overall response times and also switch costs are reduced when compared with cued task switching (Arrington and Logan 2005; Gollan et al. 2014).

The voluntary task switching paradigm enables the researcher to assess performance as not only dependent variable but also choice rates. Yet, this paradigm poses some specific methodological challenges for researchers (see Arrington et al. 2014, for a review). First, one has to infer which task was chosen and actually performed in each trial. Two variants of voluntary tasks switching have been applied. One variant is that participants can be asked to respond with different sets of response keys for each task (Poljac and Yeung 2014). Second, participants can be asked to indicate first which task to perform (task choice), and only then the target stimulus appears and participants respond to it (action selection). This so-called double registration procedure has the advantage that switch costs are typically larger than with separate response sets for both tasks, and it allows the researcher to manipulate the time between task choice response and stimulus appearance as preparation time.

The second challenge is that one has to make sure that participants do not simply perform only one task but actually engage in task switching, so that switch rates and also performance in switch and repetitions trials can be assessed. To induce sufficient task switches, participants were often instructed to choose each task in around half of the trials and to choose tasks in random order, such as if flipping a coin (e.g., Arrington and Logan 2004, 2005). Indeed, without any instruction or manipulation to engage in switching, switch rates would be below 10% (Kessler et al. 2009). Interestingly, with randomness instruction, participants are usually able to perform each task equally often, yet switch rates are usually below 50%, indicating that participants are not able to follow the randomness instruction but have a bias to repeat tasks. The size of the repetition bias varies often with manipulations that affect performance (e.g., larger switch costs are related to a larger repetition bias, i.e., lower switch rates, e.g., Mayr and Bell 2006).

Recently, a number of different manipulations were introduced to make sure that participants engage in task switching without asking them to choose tasks in random order. For example, Fröber and Dreisbach (2017) used a hybrid version of voluntary and cued task switching. They intermixed trials in which a task cue indicated the required task with trials in which participants voluntarily decide with task to perform. Thereby, the amount of cued task switches varied, such that either 75%, 50%, or 25% of the trials were cued, while the number of task repetitions and switches was roughly the same in the cued conditions. As a result, the switch rate in the voluntary choice trials varied such that participants choose task switches more often the larger the amount of cued trials.

2.4 Summary

In the last 25 years or so, starting with seminal studies by Allport et al. (1994), Meiran (1996), and Rogers and Monsell (1995), a number of different versions of the task switching paradigm have been designed. All experimental paradigms share the basic idea of comparing performance in switch conditions and task repetition conditions, but they differ in the specifics of how they achieve this goal. As we discuss below, the paradigms have different strengths with respect to how the overarching issue of "executive" cognitive control can be examined. Given that switch costs themselves do not represent a process-pure measure and include components that are related to involuntary aftereffects of having performed a different task previously (see Sect. 4), it is of major importance to examine how active preparation processes can influence and in fact reduce task switch costs. This preparatory reduction of switch costs is often seen as the hallmark of executive, active (or "endogenous") control of task set (see Monsell 2003; Vandierendonck et al. 2010), and it has been observed in each version of the task-switching paradigm. In the next section, we turn to this issue of task preparation.

3 Proactive Control: Task Preparation

A highly relevant research questions refers to whether cognitive control processes in task switching are triggered *in response to* some processing conflict (reactive control) or whether it occurs *in anticipation of* conflict, such as in an upcoming switch of task ("proactive" or "active" control). Active control in task switching would require processes of task preparation, which in turn necessitates some foreknowledge about upcoming processing conflicts. Because performance costs in task switching can often be explained as effects of reactive control, which we describe in the next section (Sect. 4), it is theoretically particular relevant to demonstrate active preparation effects in task switching as these may reflect truly "endogenous" control processes (Rogers and Monsell 1995). There are two experimental variations that have been used to examine active task preparation. The first refers to the time for preparation within a given experimental trial once the identity of the upcoming task is known. The second refers to the beneficial influence of predictability of task sequences across experimental trials (i.e., relative to unpredictable task sequences).

3.1 Influence of Preparation Time in Predictable Task Sequences

Rogers and Monsell (1995) used alternating runs of two tasks (i.e., AABBAA, etc.) and presented their target stimuli (digit-letter compound stimuli) in a 2x2 grid on the screen. The target stimulus "moved" in a clockwise manner once the participant has responded to it. Because of this target location sequence on the screen, the subsequent task was fully predictable, so that, for instance, stimulus locations on the upper row required a digit classification (parity: odd vs. even) and locations on the lower row a letter classification (consonant vs. vowel). That is, with this paradigm, participants had always foreknowledge about the upcoming task. Despite the seemingly simple setup, the authors observed very substantial switch costs.

In order to examine the influence of task preparation on switch costs, Rogers and Monsell (1995) manipulated the time between the response to the previous target and the presentation of the next target stimulus (the response-stimulus interval, RSI). Because the upcoming task was predictable based on the easy sequence, a longer RSI can, arguably, be used for active preparation for the next task. Rogers and Monsell (1995) indeed observed a general benefit for longer RSIs, but for task repetition trials, this benefit was quickly asymptotic, whereas the beneficial effect of RSI for task switches was generally larger and increased even for longer RSIs. As a consequence, the switch costs, which represent the difference between switch trials and repetition trials, became progressively smaller. This preparatory reduction of switch costs represents the "signature finding" of proactive control in task switching (see Monsell 2003; Vandierendonck et al. 2010) (Fig. 4).

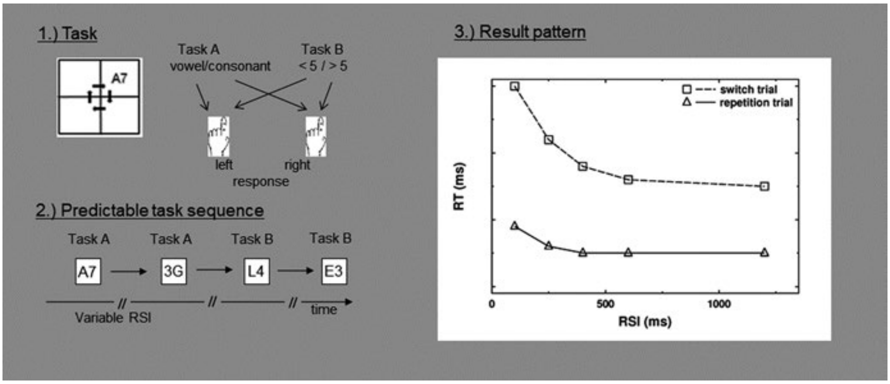

Fig. 4 Sketch of the experimental design with 1. Task and 2. Predictable task sequence and 3. the result pattern from Rogers and Monsell (1995, Experiment 3), redrawn from their table

One important finding, already evident in the data reported by Rogers and Monsell (1995), is that the switch costs remain substantial even after ample preparation time. This finding has been termed "residual" costs and has triggered empirical and theoretical development that we describe in more detail later (see Sect. 4). But the preparatory reduction of switch costs has raised some theoretical and methodological issues, too.

The preparatory reduction of switch costs has been interpreted in terms of an advance "reconfiguration" of task set (Monsell 2003), such as the activation of the new task goal and the "loading" or "implementation" of new task sets, that is, stimulus-response mappings in working memory. Obviously, getting extra time for doing so prior to target presentation should be beneficial and can explain the RSI-based reduction of switch costs.

However, during the RSI, there is also time for the previous task set to dissipate more or less "passively" (Allport et al. 1994), which could also explain some of the reduction of switch costs because with long RSI the preceding task set should no longer be strongly activated, so that it is easier to activate and implement a new task set instead. Hence, activation decay of the preceding task set and preparing and activating the new task set are alternative accounts for the same empirical findings (e.g., Sohn and Anderson 2001), and it is hard to tell them apart in this particular experimental paradigm (i.e., RSI variation in predictable task sequences).

3.2 *Influence of Preparation Time in Random Task Sequences: Explicit Task Cuing*

Meiran (1996) suggested a solution to this methodological and theoretical issue by proposing a paradigm in which the task sequence itself is random (unpredictable), but in each trial the upcoming task is indicated by an explicit task cue. He presented a smiley in a 2x2 spatial grid, and participants were asked to classify either the horizontal (left-right) position or the vertical (up-down) position of the stimulus, depending on an explicit cue. As task cue, he presented arrowheads on the left and right for the horizontal task and on the upper and lower part of the spatial grid for the vertical task. With this setup, Meiran (1996) could manipulate the interval between the explicit cue and the target stimulus (CSI) independently from the overall interval. For example, when the overall interval, that is, the RSI, is 1000 ms, the CSI could be either 100 ms or 900 ms, so that the cue is shifted in the RSI either toward the next target stimulus (short CSI) or toward the preceding response (long CSI). This way, there is a concomitant variation of the response-cue interval (RCI), which is inverse to the variation of CSI, and this allowed Meiran to manipulate preparation time while holding "dissipation time" constant (i.e., constant RSI). Meiran (1996) found that performance generally improved with long CSI and particularly switch costs were reduced with long CSI (see also Koch 2001, Experiment 4). This cue-based preparatory reduction of switch costs in random task sequences thus confirmed RSI-based reduction of switch costs with predictable task sequences observed by Monsell and his colleagues (see Monsell 2003; see Kiesel et al. 2010, and Vandierendonck et al. 2010, for reviews).

The explicit task cuing paradigm has become a major paradigm for studying proactive cognitive control in terms of preparation in task switching. There is also a substantial body of evidence coming from studies using cognitive neuroscience methods (e.g., EEG, functional brain imaging, brain lesion patients) showing that a specifiable brain network mainly including frontal and parietal brain regions are heavily involved particularly in active task preparation (for reviews, see, e.g., Karayanidis et al. 2010; Ruge et al. 2010). In the present chapter, we focus mainly on behavioral data and the corresponding cognitive theories, but the reader interested in the neuronal basis of these behavioral effects is referred to Richter and Yeung (2014) and to the chapter by Brass and De Baene (Chap. 7, this volume).

3.2.1 Preparation vs. Dissipation of Task Sets

Importantly, the explicit task cuing paradigm can be used to examine the potential influence of activation dissipation of the previous task set (sometimes also called "task-set decay"; see Horoufchin et al. 2011). Specifically, when the CSI is held constant and short, the RCI can be varied, so that the RSI as the overall dissipation time can be long or short, whereas preparation time is always short, thus isolating the influence of dissipation. Meiran et al. (2000) showed that switch costs indeed got smaller with longer RCI (see also Altmann 2004; Koch 2001; Koch and Allport 2006), showing that there are processes going on during the RSI that can decrease the size of switch costs independent of preparation. Hence, these RCI effects confirm the suspicion that RSI manipulations in predictable task sequences include the influence of processes beyond active preparation (we return to this issue in Sect. 4).

3.2.2 Switch-Specific vs. Task-Specific Preparation

After having established empirically that there is cue-based preparatory reduction of switch costs, it seems plausible to assume that this preparation is to some degree *specific* for a task switch. This idea is consistent with an early theoretical account already proposed by Rogers and Monsell (1995). They suggested that task-set reconfiguration is required only in switch trials because in task repetitions, the same task set can remain in place. It should be noted though that preparation of a task switch cannot be separated easily from preparing a new task. Put differently, we can ask if participants really prepare for a switch itself or rather for the new task in a switch trial. When switching only between two tasks, this question cannot be answered because of the basic asymmetry of task repetitions and task switches (see Koch 2008). That is, in repetitions, knowing that the next trial is a repetition also necessarily identifies the task. However, knowing that the next trial will be a switch trial does not necessarily identify the next task unless there are only two tasks, so that the alternative task is clearly specified.

However, with more tasks, it is possible to examine if there is "true" switch-specific preparation even in the absence of knowing the identity of the next task. This issue has first been examined by Dreisbach et al. (2002, Experiment 4 and 5), who presented probability cues for one of four tasks. The cues could be either task-specific or transition-specific. The authors reasoned that with a highly likely switch, the previous task could already be inhibited even though the identity of the to-be-switched-to task is not yet known. However, the authors found only very little evidence for pure switch-specific preparation, and later studies found likewise only small effects with transition-specific cues if these cues did not specify the task itself because there are more than two tasks (unlike with transition cues when there are only two tasks; see Forstmann et al. 2005, 2007; Schneider and Logan 2006; Van Loy et al. 2010).

For example, Koch (2008, Experiment 1) used three tasks in an explicit cuing paradigm, but he presented them in predictable, double alternating sequences (i.e., AABB schema) in most blocks of trials, but there were also blocks with random, unpredictable sequence. This design made it possible to examine the beneficial influence of predictability relative to the random, unpredictable "baseline" condition. For task repetitions, for which both the abstract transition ("repetition") and the identity of the next task was predictable, predictability resulted in a 120 ms benefit relative to the random baseline. However, for switches, for which only the transition but not the identity of the next task was predictable, there was only a small (but still significant) predictability benefit of 36 ms. Hence, pure switch-specific preparation seems to convey comparatively small benefits (see also Aufschnaiter et al. 2021; Nicholson et al. 2006). This suggests that the main role of preparation is in the activation of the task set for the next trial, whereas abstract knowledge about the sequential transition itself is not highly effective, even though it is possible that some performance benefit can be produced by inhibiting the just executed task in order to facilitate an upcoming task switch. This possibility of "proactive" inhibition is still debated (see Mayr and Keele 2000; cf. Elchlepp et al. 2016; Gade and Koch 2014; Scheil and Kleinsorge 2014, for a discussion; see also Sect. 4).

3.2.3 Role of Cue Processing: Task Switching or Cue Switching?

The finding of a preparatory reduction of switch costs has raised the issue of whether there are “abstract” switch-preparation mechanisms (which could theoretically consist of inhibition of the previous task) or whether switch-specific preparation is always preparation for a new task. However, an even more radical approach has been suggested by Logan and Bundesen (2003), who suspected that the empirical finding of a cue-based preparatory reduction of switch costs is not even related to task switching. Instead, these authors proposed that participants in an explicit task cuing paradigm adopt a “compound stimulus” strategy and encode cue and target stimulus together and respond to this compound. For example, the cue “PARITY” and the target digit 3 would be associated with the response “odd” (and the corresponding key press), whereas the cue “MAGNITUDE” and the same target would activate a “smaller than 5” response and key press. If viewed in this way, then responding to “compound cues” would explain the basic phenomenon of switch costs even if participants did not form abstract categories or higher-order task set. This is because in repetition trials the cue repeats, so that one component of the compound is already primed in short-term memory and hence the new compound can be encoded more quickly compared to compounds that entail a new cue (and thus instruct a task switch). With a longer CSI, there is more time to encode the cue in advance so that the compound is formed more easily, thus reducing or eliminating the difference between switched and repeated cue conditions.

Logan and Bundesen (2003) argued that they could explain the basic switch cost and its cue-based reduction by this simple association learning account (see Forrest et al. 2014, for a discussion). Moreover, they tested this account by introducing two cues for each task, so that a task repetition could be indicated by a repeated cue (i.e., the standard case) or by the alternate cue for the same task. This way, it was possible to partially dissociate cue switching from task switching. Logan and Bundesen (2003) found that performance in task repetitions with switched cue was hardly any better than in task switches (which are necessarily cue switches, too), suggesting that there are only small (if any) “true” task switch costs and that task switching mainly examines the influence of cue priming (Schneider and Logan 2005).

The issue of cue priming vs. task switching has raised substantial interest in task-switching research (see Jost et al. 2013; Koch, Poljac, et al. 2018, for more recent reviews). Generally, there seem to be little doubt that priming processes at the level of cue encoding contribute to performance in the explicit cuing paradigm. However, most (if not all) subsequent studies using this 2:1 cue-to-task mapping procedure demonstrated substantial “pure” task switch costs (e.g., Gade and Koch 2008; Mayr and Kliegl 2003; Horoufchin et al. 2011; Koch, Lawo, et al. 2011). For example, Monsell and Mizon (2006) never presented cue repetitions, so that both task repetitions and switches were always accompanied by cue switches, and these authors found clear switch costs that got smaller with longer preparation time (Lavric et al. 2008). In addition, Forrest et al. (2014) directly compared the result patterns when participants were explicitly instructed to respond to the compound stimulus (i.e., the task cue and target stimulus as a "compound" target) or had to learn by trial-and-error how to respond correctly to the compound stimulus with a standard task switching instruction. Effects of task switching (though confounded with cue switching), CSI (preparation time), and response congruency differed substantially across these two instruction (i.e., learning) conditions, ruling out the assumption that task switch costs merely result from "automatic" cue priming and suggesting instead the involvement of task representations when being instructed to apply such representations. Similar conclusions are also suggested from studies of Dreisbach and colleagues (e.g., Dreisbach et al. 2007). Thus, even though the strictly associative approach proposed by Logan and Bundesen (2003) has not found substantial empirical support, it is also clear that the contribution of cue processing itself needs to be part of theoretical models (see Sect. 5).

Recently, Frings et al. (2020) considered task switching in a so-called "binding and retrieval" account assuming that all features of a trial are bound together and might be retrieved in the following trial. In this framework, the effects of cue repetitions in addition to task repetitions can be easily explained as repeating features in consecutive trials. Interestingly binding and retrieval processes are presumably not restricted to representations of stimuli and responses, but also cognitive control settings might be bound and retrieved in the subsequent trial. Recently, Dignath et al. (2019) demonstrated such binding and retrieval only for attentional control states in prime-target tasks, yet evidence for binding and retrieval of abstract control settings regarding task switching is still missing. Nevertheless, the reduction of switch costs with longer CSI might reflect the fact that with longer CSI, there is more time to encode the task cue in advance and to retrieve the cue as well as the task set of the previous trials in case of cue repetitions. Thus, switch costs in this framework would mainly reflect task repetition benefits due to binding and retrieval of the previously active task set.

3.2.4 The Role of Action Execution: Preparing vs. Executing Tasks

A different approach to the role of cue processing in task switching has been taken by studies that examined whether cue-based preparation for a task switch alone can already result in reduced switch costs. Such studies used variants of the go/no-go methodology, in which the cue could be followed by a go trial or a no-go trial. Note that the explicit cuing version of the task-switching paradigm allows the researcher to introduce no-go trials either as "cue-only trials" (Swainson et al. 2017), trials with a neutral stimulus (Schuch and Koch 2003, Experiment 1B), or as trials with an added no-go signal (e.g., a tone, Philipp et al. 2007; Schuch and Koch 2003). An important feature in this design generally is that the next task is explicitly cued. The critical question is whether cue-based preparation is powerful enough to reduce switch costs even if the prepared task is not actually executed because the trial turned out to be a no-go trial.

This no-go approach has been taken by Schuch and Koch (2003). In their study, the target stimulus was accompanied by a high vs. low tone, and the no-go tone occurred on 25% of the trials. Hence, a go trial was very likely. The authors found that switch costs were quite substantial following go trials, but strongly reduced if the previous trial turned out to be a no-go trial. Note that these authors manipulated the CSI to make sure that participants actually used the available preparation time before the onset of the go/no-go signal, and they found that performance in go trials was generally much better with long CSI than with short CSI, indicating that participants used the CSI for task preparation. Because the occurrence of go vs. no-go signal was not predictable, it follows that participants must have prepared on no-go trials, too. Hence, preparation for a task alone in one trial did not result in strong effects on task performance in the subsequent trial (see also Koch and Philipp 2005). In a subsequent variation of the paradigm, Philipp et al. (2007) changed the no-go paradigm into a "go-signal paradigm" by asking participants not to respond to the target until they get a go-signal, but in a small fraction of trials, there was a no-go signal instead. This paradigm allowed the researcher not only to manipulate the CSI for task preparation but also the go-signal delay, which indexes preparation of a task-specific response. These authors found that even with a prepared response, after a no-go trial the costs of switching the task relative to repeating the just prepared but not executed task were greatly reduced compared to trials following a go trial, in which a task was prepared and executed.

The finding of reduced switch costs following no-go trials has attracted much research attention. Basically, the main finding has been shown to be quite robust (e.g., Desmet et al. 2012; Hoffmann et al. 2003; Lenartowicz et al. 2011; Los and Van der Burg 2010; Verbruggen et al. 2005). However, the amount of switch cost reduction after no-go has been found to depend on methodological details, and substantial switch costs could be found even after no-go trials (Swainson et al. 2017). Recently, Swainson et al. (2019) suggested that task preparation alone may be sufficient to produce subsequent switch costs. They argued that the often observed reduction of switch costs after trials in which the prepared task was not executed speaks in favor of a theoretical two-stage account of task switching, in which a first stage prepares for a new task (called task-set reconfiguration by Rogers and Monsell 1995; or rule shifting by Rubinstein et al. 2001), but that this new task set still needs to be fully implemented during actually executing the task by selecting and producing the required response itself (see Kiesel et al. 2010, for a review, and see also Sect. 5).

Irrespective of the issue of whether task preparation alone may be sufficient to produce subsequent switch costs, there is one additional aspect of the no-go paradigm that deserves brief consideration here, and this is that the no-go signal might lead to inhibition of the just prepared but not executed task. Usually, go/no-go methodology is applied to single-task contexts and interpreted as a method for studying response inhibition. In task switching, a no-go signal necessarily results in inhibition of a response, but it might also inhibit the prepared task. Inhibition of prepared tasks could easily explain reduced switch costs after no-go trials. It would also be consistent with the finding of Schuch and Koch (2003; Koch and Philipp 2005) that this reduction of switch costs after no-go trials occurred mainly because performance in task repetitions became worse, whereas performance in the actual task-switch trials was much less affected by whether the previous trial was a go trial or a no-go trial.

However, Schuch and Koch (2003) and Philipp et al. (2007) also examined the influence of no-go trials in a different paradigm with three tasks, in which there was never an immediate task repetition. They examined the phenomenon of n-2 task repetition costs (Mayr and Keele 2000; see Koch et al. 2010, for a review), which denotes worse performance in n-2 task repetition sequences (e.g., ABA) relative to n-2 non-repetitions (e.g., CBA). N-2 task repetition costs are consistent with the idea that switching to a new task is associated with inhibiting the previous task, so that n-2 repetitions require switching back to a task that has been just switched away from, so that it should still remain in an inhibited state (see Fig. 5 for illustration). Note that persisting activation accounts would predict an n-2 task repetition benefit, so that n-2 repetition costs speak in favor of an inhibitory aftereffect.

Schuch and Koch (2003) showed substantial preparation benefits in go trials based on increased preparation time (i.e., CTI), and this was independent of whether the previous trial was a go trial or a no-go trial. Notably though, the n-2 repetition costs were greatly reduced after no-go trials, suggesting that these costs are not based on previous task preparation (existent on both go and no-go trials) but on previous task execution (only on go trials). Moreover, Philipp et al. (2007) showed this substantial reduction (or even elimination) of n-2 task repetition costs even when the response itself could be fully prepared (i.e., with a long go/no-go-signal

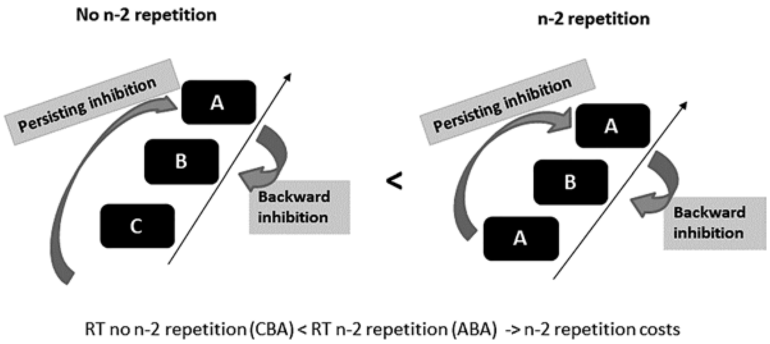

Fig. 5 N-2 repetition costs indicate that performance in ABA sequences (right side) is hindered (longer RTs, larger error rates) compared to performance in CBA sequences (left side). It is assumed that when performing a task, the previously implemented task set is inhibited ("backward inhibition"). This inhibition persists and interferes with switching back to a more recent task set in ABA sequences than to a task set for which the persisting inhibition occurred earlier (and thus decayed more), as in CBA sequences

delay) in a preceding no-go trial. Note that "self-inhibition" of the just prepared task in a no-go trial could not explain the finding of reduced n-2 task repetition costs because such a "n-1 task" inhibition should not affect n-2 task repetition costs. This suggests that the underlying mechanism of reduced switch costs when switching between two tasks is likewise not related to inhibition of prepared but not executed tasks. That is, overall, the data are consistent with an account that assumes that task preparation reflects an important cognitive process, but that other processes related to selecting and executing the actual task-specific response (often subsumed under the term "task implementation") are equally important in task switching.

3.3 Preparation Based on Task Predictability Instead of Preparation Time

Preparation does not only take place when a cue instructs the required task but also when a task can be predicted based on the previous learning history. Here we focus on two types of predictability: Task-based predictability refers to the role of learning sequential transitions across tasks in task switching, whereas time-based predictability refers to the role of learning temporal contingencies within tasks.

3.3.1 Preparation Based on Task-Based Predictability

Early studies on task switching used predictable task sequences. For example, Jersild (1927) compared performance in single-task conditions (AAA, BBB, etc.) with that in strictly alternating task conditions (ABABAB, etc.). With strict alternation, the identity of each subsequent task is determined in advance and thus fully predictable. The same is true for the alternating-runs paradigm used by Rogers and Monsell (1995; see also Koch 2003; Monsell et al. 2003) and for other paradigms in which participants performed always pairs of tasks that either comprised a task repetition (AA) or a task switch (BA), as used, for example, by Allport et al. (1994), Goschke (2000), or Sohn and Carlson (2000). Preparation in this setup was usually examined by manipulating the RSI in these predictable sequences (see also Kray and Lindenberger 2000, for such a study with reference to age-related effects on task switching). Note though that the role of predictability for preparation was not studied itself because predictability was just used as a methodological tool in order to be able to meaningfully manipulate the RSI as time for preparation.

Unlike such studies, early studies on task-based predictability introduced a fixed sequence of tasks, in which the upcoming tasks can be predicted, and compared performance in such predictable tasks with that in random tasks (Gotler et al. 2003; Heuer et al. 2001; Koch 2001). For example, in the study by Koch (2001), three different tasks were presented in a fixed order of nine tasks, so that each task transition (including the immediate repetition of a task) occurred equally frequently. Notably, each task was also cued in each trial, with short CSI. After several blocks of practice with this fixed task sequence, the fixed sequence was replaced with a novel sequence with similar frequency information, so that previously learnt predictions about upcoming tasks in the fixed sequence could no longer be applied. This change in the task sequence resulted in a significant negative transfer effect, that is, performance got worse in the transfer block relative to the training blocks with the fixed sequence. This paradigm thus borrowed implicit-learning methodology (see Schwarb and Schumacher 2012, for a review) for the study of learning task sequences. In fact, the presence of a fixed, repeating task sequence was not announced (it was thus an incidental learning situation), and in a post-experimental interview, participants could not reproduce relevant knowledge of the sequence, thus qualifying this task predictability effect as an implicit learning effect (Koch 2001, Experiment 1 and 2). Similar experimental designs showed comparable findings, that is, participants were able to acquire and use the sequential predictability build in the task sequence and improved their performance based on this predictability (see also Koch et al. 2006).

However, these preparation effects based on implicit learning were not specific to task switches, that is, both switches and repetitions benefited alike from learning, so that switch costs remain unchanged. Thus, it remained possible that the lack of switch specificity of task predictability effects in these studies was due to the "implicit" character of sequential task preparation and that implicit and explicit sequence knowledge might rely on different mechanisms. To test the role of explicit sequence knowledge in such task-sequence learning studies, Koch (2005) used a simple alternating runs paradigm (AABB) and instructed participants to perform this sequence. In this explicit learning condition, participants produced very strong performance benefits based on the predictable sequence relative to a randomized transfer sequence, but, again, this predictability benefit presented itself as an equal preparation effect for task switches and repetitions. That is, despite massive learning effects, the switch costs were not significantly changed based on sequential task predictability (sometimes also called "foreknowledge"; see Sohn and Carlson 2000).

3.3.2 Preparation Based on Time-Based Predictability

In addition to predictable task sequences, also other features of the environment can serve to predict the upcoming task. For example, the system response time when clicking on a web link is often informative – the longer the system delay, the more likely it is that the loading of the webpage might fail (Thomaschke et al. 2015). In experimental studies, Thomaschke et al. (2011; see Thomaschke and Dreisbach 2015, for a review) demonstrated that time, in terms of duration of a time period, can be used to predict upcoming events. In these studies, a variable time interval (often termed foreperiod) precedes the presentation of stimuli. Importantly, the duration of the time interval predicts the latter event such that, for example, a short time interval is frequently paired with stimulus A, while a long time interval is frequently paired with stimulus B. Participants incidentally learn this time-event correlation and exploit it to prepare responding to the predicted stimulus (Thomaschke and Dreisbach 2013).

Recently, Aufschnaiter, Kiesel, Dreisbach et al. (2018) transferred the time-event correlation paradigm to task-switching settings. In their study, participants switched between categorizing a digit as odd/even (parity task) or smaller/larger 5 (magnitude task) and the color of the digit served as task cue. The digit occurred after a variable time interval of 500 ms or 1500 ms, and each time interval was paired more frequently with one or the other task. Participants responded faster to frequent rather than infrequent time-task combinations, indicating that they incidentally learned that elapsed time predicted the upcoming task requirement.

Further, Aufschnaiter et al. (2021) demonstrated that preparation due to time-based predictability occurs also when the time interval predicted whether a task switch or a task repetition will follow irrespective of task identity. The authors interpreted this finding by assuming inhibition for the just-performed task in case that task switches are predicted. Yet, in additional analyses considering N-2 repetitions (ABA) compared to N-2 switches (CBA), they did not find evidence for N-2 repetition costs. Thus, the assumption of inhibition processes in time-based predictability is less stringent, and the nature of the assumed inhibition processes is still unclear.

Finally, temporal predictability does not only impact on task performance but also influences task choices. Jurczyk and colleagues (2020) applied a hybrid version of voluntary and cued task switching. In the cued trials, the short or long time interval (foreperiod) prior to stimulus occurrence predicted the task with either 100% or 80% contingency. In the free choice trials, participants were asked to freely choose one of the tasks, while the stimuli for both tasks either occurred after the short or long time foreperiod. In both contingency conditions, foreperiods had an impact on task choices: After a short/long foreperiod, participants performed the task more often that was more frequently paired with the resp. foreperiod in the cued task switch condition. Taken together, this study shows that participants learned the time-based predictability in cued trials and used this information to prepare for the respective task set – indicated by performance advantages for frequent time-task combinations and by time-compatible task choices.

Similar to the impact of task-based predictability, preparation due to time-based predictability improves performance in switch and repetition trials to a similar degree, thus not reducing switch costs. These results suggest that preparation based on a variation of preparation time with explicit task cues is more likely to produce stronger benefits for switches than for repetitions (thus reducing switch costs) compared to preparation based on "implicit" cues, such as sequential task predictability and time-based predictability. One might therefore wonder whether preparation processes based on explicit knowledge (e.g., based on explicit task cues or explicitly instructed task order) differ from the preparation processes based on implicit knowledge acquired based on regularities of tasks or timing and tasks. Currently, the exact reasons for this difference in terms of effectiveness of different types of task preparation to reduce switch costs in task switching are not fully understood. Generally, it is a relevant question when preparation is effective and why preparation is usually not optimally effective in terms of eliminating switch costs altogether (see Sect. 4).

For example, it has been speculated that preparation, when it occurs at all, is usually very effective, but it does not occur on all trials, so that task-switching performance is typically a mixture of effectively prepared and entirely unprepared trials (i.e., failures of preparation), with the latter explaining why there are switch costs (De Jong 2000; Nieuwenhuis and Monsell 2002). We return to this issue below (Sect. 4), but first turn to time-based predictability in voluntary task switching.

3.4 Preparation in Voluntary Task Switching

Preparation in cued and predictable task switching based on increasing the preparation time reduces switch costs. Yet, even with ample preparation time, so-called residual switch costs remain. In these task-switching paradigms, participants have no choice but to execute the indicated task. This is different in the voluntary switching paradigm. Here participants themselves choose which task to perform in each trial. One might assume that the voluntary choice about which task to perform would increase proactive control and thus reduces or even eliminates switch costs. Empirical results are only partly in line with this assumption. Some studies observed smaller switch costs for voluntary task switching compared to cued task switching (Arrington and Logan 2005; Gollan et al. 2014). Yet, in all voluntary task switching studies, robust switch costs emerged also in voluntary task switching settings.

3.4.1 Influence of Preparation Time in Voluntary Task Switching

In the voluntary switching paradigm, the preparation time can be varied by increasing the time between trials. Liefooghe et al. (2009) instructed participants to randomly switch between a letter task and a shape task. Participants responded to the letter task (vowel or consonant) with right-hand responses (index and middle finger) and to the shape task with left-hand responses. The response-stimulus interval (RSI) was either 100 ms or 1000 ms, and it was varied within-subject in separate blocks or between-subjects. In both conditions, switch costs were smaller for the long RSI rather than for the short RSI. Liefooghe et al. (2009) therefore concluded that participants reconfigure the task set similar as in cued task switching.

Similarly, Yeung (2010) reported a decrease in switch costs with increasing the RSI. In his study, participants switched between a shape task and a location task. In each trial, a geometrical shape was presented either in a left, middle, or right location. For the shape task (circle, square, triangle), participants responded with index, middle, and ring finger of one hand. For the location task, participants responded with spatially compatible responses with the other hand. Thus, shapes could require either a location-congruent or a location-incongruent response. This effect of response congruency impacted on performance data (RTs and error rates). More importantly, however, Yeung also assessed task choices and observed that participants chose the more difficult shape task more often than the easy location task. In addition, stimulus repetitions impacted on task choices (for a similar finding, see Mayr and Bell 2006). Consequently, Yeung assumed a complex interplay of top-down and bottom-up influences on voluntary task switching. In the following, we will discuss in more detail how task choices in voluntary task switching are influenced by top-down and bottom-up mechanisms and how task selection can be indicative for proactive control.

3.4.2 Task Selection as Proactive Control to Reduce Switch Costs

The voluntary task switching paradigm enables the researchers to consider task selection in addition to task switching performance as an indicator of proactive control. An interesting discussion refers to the question of how people generally select which task they will perform. Or more specifically, how can we explain the repetition bias – the observation that people repeat tasks more often as expected by chance when they are instructed to choose between two tasks in a random order (as if flipping a coin) and to perform both tasks around equally often (e.g., Arrington and Logan 2004). In voluntary task switching studies applying this "randomness instruction," participants seem to typically succeed in selecting each task equally often, but they also quite consistently tend to repeat tasks more often than chance (e.g., Arrington and Logan 2005; Mayr and Bell 2006).

The literature so far has provided empirical evidence for different factors influencing task selection in voluntary task switching. For instance, the repetition bias becomes stronger in conditions with shorter preparation time (Arrington and Logan 2005), increased working memory load (Demanet et al. 2010), and greater response conflict (Orr et al. 2012). These observations are consistent with the idea that top-down processes are needed to overcome the tendency to repeat tasks. However, bottom-up influences of task selection have also been demonstrated in voluntary task switching studies. For instance, stimulus repetition seems to increase the repetition bias (Mayr and Bell 2006), suggesting that stimuli themselves can prime selection of task sets. Also, people seem to be more inclined to choose the same task as the one that was first performed on the initial exposure to that specific stimulus (Arrington et al. 2010). Studies using displays containing multiple stimuli have shown that task selection is influenced by both the timing (Arrington 2008) and location of stimulus onset (Arrington and Rhodes 2010; Arrington and Weaver 2015). The strength of these bottom-up effects varies across individuals (Butler et al. 2011) and situations (Demanet et al. 2010).

Recently, Fintor et al. (2020) investigated the effect of stimulus-response (S-R) modality compatibility in voluntary task switching. Modality compatibility refers to the similarity between stimulus modality and the modality of response-related sensory consequences (e.g., vocal responses produce auditory effects, whereas manual responses often produce visual effects). In their study, participants freely chose the response modality (vocal or manual) to indicate the location of either a visual or an auditory stimulus. This could create modality-compatible mappings (auditory-vocal or visual-manual) or modality-incompatible mappings (auditory-manual or visual-vocal). As in typical voluntary task switch studies, the authors found that there was a repetition bias for the chosen response modality (producing 59% repetitions). Importantly, they also observed that modality-compatible tasks were overall preferably selected (in more than 53% of the trials).

Taken together, there is unequivocal evidence that task selection is influenced by top-down and bottom-up factors. Two different accounts have been put forward to specify the top-down and bottom-up influences of task selection in voluntary task switching.

First, Arrington and Logan (2005) assumed that two competing heuristics determine task selection. The representativeness heuristic (as top-down factor) compares a mental representation of a random sequence to the sequence of recently performed tasks held in working memory to decide what next task would make this sequence most representative of a random sequence. The availability heuristic ascribes task selection to the most active task set. Thereby task availability is determined by factors that are both top-down and bottom-up (like priming of tasks by stimulus sets, response sets, etc.). From this perspective, the repetition bias occurs because the passive availability heuristic overrules the more controlled use of the representativeness heuristic.

The second account is the chain-retrieval model by Vandierendonck et al. (2012), which provides a more formal account of task selection. The model incorporates factors representing top-down and bottom-up processes. The idea is that people retrieve chains of tasks from long-term memory based on a mental representation of randomness. When the actual performance of task sequences deviates from randomness, it is suggested that this comes as a result of either chain selection being biased by the ease of the performance (i.e., by facilitating responding in repetition trials than in switch trials) or stimulus-based priming.

The claim that task selection might depend on previous task performance is further supported by studies which show a similar effect on both measures. For example, Arrington and Logan (2005) observed that switch costs and repetition rates decrease when increasing the response-stimulus interval between trials (e.g., Arrington and Logan 2005). Further, Yeung (2010) reported data that asymmetrical switch costs, that is, differences in switch costs when switching between an easier and a more difficult task, are also reflected in participants' choice behavior. Yet, while these findings point to a connection of task selection and task performance, correlational analyses between both measures show that the bias to repeat tasks is independent of or only weakly related to the size of switch costs (Arrington and Yates 2009; Mayr and Bell 2006).

However, Mittelstädt, Miller, and Kiesel (2018) recently pointed out that the randomness instruction in the voluntary task switching paradigm is actually unfortunate if one is interested in the interplay of task selection and task performance. They developed a task-switching paradigm, in which participants could organize the task order themselves, being instructed to optimize their task performance in a voluntary task switching context. In their *self-organized task switching paradigm*, two stimuli are presented on the screen, each of them is associated with one of the two tasks. Importantly, the onset of the stimulus of the task performed on trial n-1 was delayed on trial n, and this delay (i.e., the SOA between the switch and the repetition stimulus) increased linearly with the number of consecutive repetitions. In this way, participants were set to decide to either go with a relatively easier repetition of task but wait for its task stimulus or to respond to the immediately available stimulus and hence the harder option of switching tasks. Mittelstädt, Miller, and Kiesel (2018) found that participants switched tasks when the SOA in task switches approximately matched the switch costs. They also observed that people would adjust their choice of switching depending on how big the steps of SOA were and hence how long they needed to wait for the task repetition stimulus to appear. In a further study, Mittelstädt and colleagues (2019) provided more evidence for a close link of task selection and task performance. Conditions that impacted on the size of switch costs, like manipulating the interval between trials (RSI), similarly impacted on switch rates. Moreover, switch costs and switch rates correlated negatively, suggesting that participants with larger switch costs switched tasks less often.

These finding suggests a relation between task choice and task performance, which is different from observations reported in studies that used randomness instruction (e.g., Mayr and Bell 2006; Yeung 2010). This is interesting as it suggests that in self-organized task switching conditions, people incorporate the costs of switching tasks in their task selection behavior. In fact, some evidence has been provided that also in voluntary task switching settings with randomness instructions, individual switch costs are related to individual switch rates (Mittelstädt, Dignath et al. 2018). Moreover, people seem to have some kind of preference in ways they organize their choice of task: some choose to mainly repeat tasks, while others would either partially or mainly prefer switching between tasks (Reissland and Manzey 2016). This preference is, however, for some individuals adaptive in nature: Brüning and Manzey (2018) demonstrated that individuals with high working memory capacity seem to be flexible in adopting their mode of processing to the task context. Poljac et al. (2018) showed that the tendency to repeat tasks was stronger in adolescents than in (young or older) adults.

Recent literature has also specified some other factors that influence task switching rate. For instance, mere exposure to a higher switch rate in cued task switching conditions already promotes a higher voluntary switch rate in voluntary condition (Fröber and Dreisbach 2017). Furthermore, Braem (2017) has demonstrated that rewards can influence people's switch rates: When rewarding participants more for task switches than for task repetitions in cued task switching, participants subsequently switched more often once given the choice of tasks, despite the fact that the preceding reward manipulation was not explicitly explained to the participants. Reward is of course an important aspect to consider in all behavior, and its role in task selection in task switching is gaining increasing interest. In a novel paradigm, Braun and Arrington (2018) investigated how well a cost-benefit mechanism could explain decisions in multitasking contexts. Using a reward-based voluntary task switching paradigm, in which point values are ascribed to tasks where the overall goal is to accumulate points as quickly as possible, Braun and Arrington were able to directly quantify the benefit for a task switch. The authors found that people are highly sensitive to changes in both reward and effort demands when choosing between tasks, with the task-selection process being efficient and flexible. They therefore suggested that people compute task selections based on both the reward available for selecting a task and the effort necessary to execute a task (see also Fröber et al. 2019; Jurczyk et al. 2019), making a cost-benefit mechanism an attractive candidate for explaining task selection in multitasking contexts.

Taken together, a central question of voluntary task switching research is how people choose to switch or to repeat tasks when having that choice (Imburgio and Orr 2021). One theoretical proposal is that task selection is driven by a cost-benefit mechanism that relies on computations of expected values of control (EVC; Shenhav et al. 2013). The EVC mechanism computes the expected value of options that can be chosen by determining both the task that should be performed (i.e., the identity of the control signal) and the amount of control (the intensity of the control signal) that is needed. As recruiting control is intrinsically costly (e.g., Kool and Botvinick 2014; Kurzban et al. 2013; Westbrook et al. 2013), the fundamental role of the cost-benefit mechanism is to efficiently determine effort allocation by finding optimal balance between control that is needed and reward to be expected. Basically, three major factors determine task selection: resources to be gained and lost, the probability of gaining or losing resources, and the amount of control (i.e., effort; see a recent review on mental effort by Kool and Botvinick 2018) necessary to execute the task (for review, see Shenhav et al. 2017). When applied to task selection in voluntary task switching, one could say that the costs of cognitive control are reflected in switch costs and repetition benefits, with the latter possibly reflecting avoidance of the effort to switch. Additionally, in the voluntary task switching paradigms with randomness instruction, one could say that the effort associated with task switching is being weighed against the benefit of making a sequence more random. Irrespective of the exact mechanisms underlying task selection, current evidence and theorizing suggests that task selection serves as proactive control to reduce switch costs.

3.5 Summary

Proactive control processes in terms of preparation of the respective task sets take place prior to stimulus processing and are indicated by reduced reaction times and reduced switch costs. Interestingly, preparation can operate predominantly in switch trials (reducing switch costs) or in a general manner (reducing reaction times in both switch and repetition trials). Preparation occurs whenever the required task can be predicted and there is sufficient time for preparation. Prediction thereby can occur because of instructed task sequences, cues that indicate the required task, or because of probabilistic learning of task sequences or time intervals (foreperiods) predicting the required tasks. Finally, the preparation does not only impact on performance but is also indicated in terms of task choices. Evidence in the voluntary task switching paradigm suggests that participants select tasks to reduce performance costs and increase reward, which arguably indexes proactive control.

4 Interference in Task Switching: Involuntary Cross Talk Based on Task Competition

Until now we have focused on the role of active preparation in task switching, assuming that task switching requires proactive control processes to implement a new task set. However, given that switch costs represent a sequential effect in the task-switching paradigm, we can distinguish between processes that are required to overcome switch costs and those that have caused switch costs in the first place. In the present section, we focus on the latter, taking on a perspective that is complementary to that focusing on active preparation.

4.1 Persisting Activation of Task Sets

The simplest, if not simplistic, view on switch costs is that it represents the time it takes for an active control process to "reconfigure" the task set, as it was already discussed (and refuted) by Rogers and Monsell (1995) more than a quarter of a century ago. Such a simple view would also imply that task repetitions represent a proper baseline because there is simply no task set to reconfigure when the same task needs to be repeated. However, such a view is faced with two major challenges.

First, it has been shown that performance in task repetition trials in mixed-task blocks is typically much worse than in single-task blocks, in which all trials are repetition trials by definition. This mixed-task vs. single-task difference has been termed mixing costs (Koch et al. 2005; Los 1999; Braver et al. 2003; Rubin and Meiran 2005; see Kiesel et al. 2010, for a more extensive review). Mixing costs imply that mixed-task situations require processes of active maintenance of the possibly relevant task sets and that this maintenance leads to parallel activation of the relevant task sets. If so, parallel task-set activation should lead to specific interference effects (i.e., mixing costs) that would be beyond the scope of the simple reconfiguration view. Hence, mixing costs suggest that there must be task competition even after an effective (in the sense of being successful) task-set reconfiguration process has taken place in a preceding task-switch trial.

Second, many studies have shown congruency effects in both switch trials and repetition trials. Congruency effects can arise when the task stimuli are "bivalent" and can be target stimuli for both tasks. For example, if the target stimuli are digits and the tasks require parity (odd vs. even) or magnitude (smaller vs. greater than 5) classification, then a target would be congruent if the response to it would be the same regardless of the task (e.g., if the target is 3, and both "small" and "odd" are mapped to the same response key), and it would be incongruent if the responses differ according to the currently relevant and irrelevant task (e.g., if the target is 4, and "small" and "even" are mapped to different responses); see Fig. 6. It has been shown in many studies that performance is worse on incongruent trials than on congruent trials (e.g., Kiesel et al. 2007; Koch and Allport 2006; Meiran and Kessler

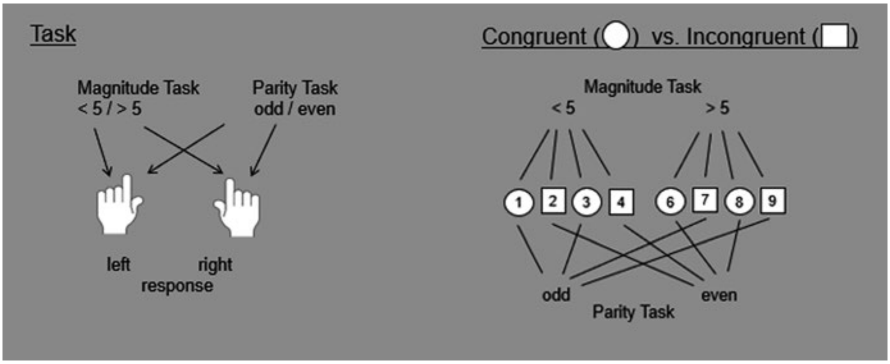

Fig. 6 Congruency effects can be observed for bivalent stimuli that can be target stimuli for both tasks. In the example, participants switch between a magnitude and a parity task. The smaller and the odd categories are mapped to the left response, the larger and the even category to the right response. This results in congruent stimuli that require the same responses in both tasks (here the digits 1, 3, 6, and 8) and incongruent stimuli that require different responses in both tasks (the digits 2, 4, 7, and 9 in this example)

2008; Rogers and Monsell 1995; Schneider and Logan 2015; Wendt and Kiesel 2008), and this congruency effect is often larger on switch trials than on repetition trials. This suggests that the competing task set is not (or even cannot be) completely de-activated, so that it is involuntarily applied to the stimulus. Interestingly, it has been found (e.g., Rogers and Monsell 1995) that responding to congruent targets can be even slower than responding to "univalent stimuli" (i.e., stimuli that are targets for one task only), suggesting task conflict in congruent trials presumably because the target activates both tasks it is associated with.

Further, congruency effects are larger in conditions in which congruent targets occur more frequently than incongruent targets (Braverman and Meiran 2015; Bugg and Braver 2016; Schneider 2015). This influence of proportion congruency on the size of congruency effects is further in line with the assumption that the irrelevant task set remains active to some degree, whereby some proactive control mechanism balances the amount of remaining task-set activity depending on overall utility of the currently irrelevant task set.

However, there is also evidence that parts of the congruency effects result from more automatic, stimulus-triggered processes. Meiran and Kessler (2008) noted that congruency effects are restricted to tasks with familiar response categories and do not occur for novel, arbitrary response categories. Further, congruency effects are not affected by task switching practice (Strobach et al. 2020), whereas task-switch costs decrease with practice, suggesting that task-set activation and deactivation/inhibition is facilitated. In addition, stimuli that occur more frequently in the alternative task context induce larger congruency effects (Kiesel et al. 2007), suggesting that associative bindings of stimuli and responses might be one cause of congruency effects. We will come back to the binding account later in this chapter (see Sect. 4.3).

The notion that task sets are active in parallel and cannot easily be deactivated has led to the concept of task set inertia, TSI (Allport et al. 1994), as one major account of switch costs. If task sets remain active over time, then a task switch is difficult because the competing task set is still active and needs to be overruled. Allport and Wylie (2000) proposed that this TSI can result in positive priming in case of a task repetition, but residual activation could also interfere if it needs to be overcome in case of a task switch. For example, evidence for TSI at the level of visual target-selection processes has been found in eye-tracking studies, where previously relevant target attributes have been shown to attract eye gaze even in task-switch trials, in which the relevant target attributes changed (e.g., Longman et al. 2013; Mayr et al. 2013). However, in addition to persisting task-set activation, Allport and Wylie (2000) suggested that there may also be persisting inhibition of the currently irrelevant task set, which renders its reactivation later on more difficult (similar to negative priming; see, e.g., Frings et al. 2020, for a recent overview of such sequential effects). In the present section, we discuss a number of effects that can be viewed as expression of such between-task competition and its aftereffects.

4.2 Persisting Inhibition of Competing Tasks

Most models either focus on the role of persisting activation in task competition (Altmann and Gray 2008) or are agnostic with regard to the role of activation vs. inhibition. However, there is some empirical evidence that supports Allport and Wylie's (2000) proposal that one component of TSI is persisting inhibition. Specifically, evidence comes from studies using three tasks and examining the influence of n-2 task repetition (e.g., task sequences of the ABA type) vs. n-2 task switches (e.g., CBA sequences). Mayr and Keele (2000) used a set of perceptual judgment tasks and found a robust performance cost when participants switch back to a task that they have abandoned recently (e.g., ABA sequence) relative to conditions in which the switch away from the current task was less recent (CBA). They termed this effect "backward inhibition" of tasks. In order to separate the label of an empirical effect from its theoretically proposed underlying mechanism, it has become more common to refer to this performance costs as n-2 (or lag2) task repetition cost. Note that the "experimental beauty" of n-2 task repetition costs lies in the fact that a persisting activation account would predict a benefit of n-2 task repetitions, due to residual activation of the task performed in trial n-2, so that n-2 task repetitions costs can be safely attributed to an inhibitory aftereffect of switching away from a task. Hence, the widely shared assumption is that participants inhibit the previous task when they have to switch to a new task because the task performed just before represents a strong competitor which is actively "deactivated," that is, inhibited (Koch et al. 2010, for a review).

The n-2 task repetition cost has become a robust marker of inhibition in the sequential selection of tasks and task sets. It has been demonstrated across a variety of types of tasks (e.g., perceptual tasks, cognitive tasks) and under many different experimental conditions, such as different intertrial intervals, such as RCI (Gade and Koch 2005) and CSI (Gade and Koch 2014; Mayr and Keele 2000; Philipp et al. 2007; Schuch and Koch 2003; Scheil and Kleinsorge 2014). More recently, it has been shown that n-2 repetition costs are reduced and can even be eliminated with extensive practice, suggesting more efficient task selection with overlearnt tasks (Grange et al. 2019). Moreover, Sexton and Cooper (2017) have presented a computational parallel distributed processing model that can account for n-2 task repetition costs using inhibition of competing "task nodes" (see Sect. 5).

One challenge with n-2 task repetition costs is that not only tasks can repeat or switch across trials but also other elements, or "features," of the tasks, such as cues, targets, and responses. Mayr and Keele (2000; see also Mayr 2002) have already discussed this issue and concluded that even when taking other potential sources of repetition priming into account, there remained a sizeable contribution of task inhibition to n-2 task repetition costs. For example, Altmann (2007) has shown that n-2 task repetition costs occur even when a 2:1 cue-to-task mapping is used, so that an n-2 task repetition is indicated by the alternate cue for the n-2 task (ABA), consistent with other, similar findings (Gade and Koch 2007; see also Mayr and Kliegl 2003). More complex repetition effects with respect to target and response repetition across trials have been examined by Gade et al. (2017), Grange et al. (2017), and Kowalczyk and Grange (2020). These authors found that some part of n-2 task repetition effects are indeed due to episodic retrieval effects; however, even after considering such retrieval effects at the level of stimuli and responses, there remained a significant n-2 repetition effect at the task level. This is consistent with the early assessment by Mayr (2002) and indicates that n-2 task repetition costs, despite being no "pure" measure of task inhibition, still represents a valid empirical marker for inhibitory processes in task switching, as already suggested by Allport and Wylie (2000) in their TSI model.

4.3 *Dissipation of Task Competition vs. Effects of Temporal Distinctiveness in Episodic Retrieval?*

It should be noted that task inhibition, as assessed with n-2 task repetition costs, do not represent an "absolute" measure of inhibition but only a relative measure, indicating an inhibitory disadvantage of the n-2 task repetition relative to tasks that have been performed less recently. Therefore, even inhibited tasks remain active to some degree. Consequently, notwithstanding the issue of persisting inhibition, the more common assumption is that much of the task competition that creates interference and switch costs is due to lingering persisting activation of the competing task.

We have already discussed in Sect. 3 that the time between trials can be used for active task preparation if the identity of the upcoming task is known or predictable. This sequential predictability was exploited by Rogers and Monsell (1995) when varying the RSI in their predictable runs paradigm. However, later studies using cued task switching with random (unpredictable) task sequences demonstrated that switch costs decrease with long intertrial intervals even when the identity of the task in the next trial was not known, that is, when the cuing interval was short (say, 100 ms) and the response-cue interval (RCI) between the preceding response and the current cue was either long or short (say, 1000 ms vs. 100 ms). This RCI effect has been explained by assuming that task-set activation decays passively over time (e.g., Koch 2001; Koch and Allport 2006; Meiran et al. 2000; Sohn and Anderson 2001). However, later studies presented data that were not fully consistent with this activation-decay interpretation (Altmann 2005). For example, Horoufchin et al. (2011) demonstrated that the mere passage of time does not seem to explain the effects.

More specifically, Horoufchin et al. (2011) varied the RCI either in a blocked way (i.e., RCI constant within blocks but varied across blocks) or a random way and found that switch costs were more or less constant with blocked RCI. With random RCI, the authors found the same results for those trial sequences in which the RCI level in the current trial was the same (i.e., unchanged) relative to the previous trial. Yet, Horoufchin et al. (2011) found the reduction of switch costs when the RCI changed from one trial to the next. Interestingly, the pattern of switch costs actually did not suggest that a long RCI improved performance on task switch trials but rather impaired performance in task repetitions, suggesting a specific loss of repetition priming. To explain their findings, the authors proposed that episodic retrieval processes contribute to switch costs and that repetition priming is in part due to retrieval of the task in the previous trial. If the preceding RCI was long and the current RCI was short, then the last task "stood out" in terms of temporal context, so that it was easy to retrieve. However, if the preceding RCI was short, but the current RCI was long, then the previous task (in trial n-1) is temporally closer to the task in trial n-2 than to that in the current trial. This results in a loss of temporal distinctiveness of the previous task episode and thus reduces the chance to efficiently retrieve the previous task, and hence the retrieval benefit in task repetitions is reduced. This temporal distinctiveness account thus refers to the ratio of subsequent RCIs rather than the absolute duration of the current RCI. Further experiments supported Horoufchin et al.'s (2011) proposal, and subsequent experimental and modeling work by Grange (2016; Grange and Cross 2015) has confirmed it and shown that it is less compatible with a model assuming passive activation decay and more consistent with a model based on temporal distinctiveness in episodic memory.

4.4 Contribution of Feature Bindings in Task Switching: I. Effects of Item Repetition

Interference effects due to remaining task-set activation or due to persisting inhibition indicate aftereffects of previously implemented cognitive control mechanisms. In addition to these types of interference effects, there is also evidence for more memory-based interference because feature binding processes will result in "bindings" of potentially relevant features, such as stimuli, responses, cues, and even task sets themselves, which can be later associatively retrieved (i.e., re-activated) when the respective feature is activated again.[1]

Evidence for such episodic repetition effects was demonstrated by Gade et al. (2017) in an n-2 task repetition context. The authors re-analyzed data of eight experiments on n-2 repetition costs (some were published before in Gade and Koch 2014) and additionally considered the impact of stimulus repetitions versus stimulus switches in trial n-2 and trial n. A linear mixed model and an analysis of effect sizes indicated that n-2 repetition costs occur mainly for stimulus switches and are mostly absent or even reversed for stimulus repetitions. Based on these results, the authors hypothesized that n-2 repetition costs might be explained by episodic retrieval instead of inhibition processes.

Similarly, other authors suggested that switch costs might indicate associative retrieval processes instead of task-set reconfiguration processes. Evidence for this suggestion was reported by Logan and Bundesen (2003, 2004) and Mayr and Kliegl (2003) by using a 2 (task cue) to 1 (task) mapping. For example, in the study of Mayr and Kliegl (2003), participants categorized either the color or the shape of objects. Task cues were the letters G and S for the color task and the letters B and W for the shape task. By using two task cues per task, it is possible to compare task switch trials that necessarily involve cue switches with task repetition trials that involve cue switches (e.g., repetition of the color task instructed by the task cue G in trial n-1 and the task cue S in trial n) and task repetitions that involve cue repetition. Results on switch costs when comparing tasks switches and task repetitions with cue switches are mixed. While Mayr and Kliegl (2003) observed switch costs in most of their experiments, Logan and Bundesen (2003, 2004) did not observe such "pure switch costs" and consequently questioned the assumption of task-set reconfiguration processes. In response to this debate, Monsell and Mizon (2006) identified switch probability as an important factor. "Pure switch costs" are larger when task repetitions are frequent. In contrast, when tasks switch frequently, "pure switch costs" are small or even absent. This result can be explained twofold. It might be that when tasks switch frequently, participants hold both task sets active (like suggested by Meiran 2000), or alternatively, participants might start to prepare a task switch even prior to the task cue because they generally expect a task switch, but this hampers the task repetition benefit and thus reduces switch costs. Importantly, the study of Monsell and Mizon (2006) shows that if task repetitions are more frequent than task switches, participants seem to reconfigure task sets. In these conditions, switch costs (while controlling for cue switches) are robust (see also

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[1] Please note that it is difficult to differentiate very clearly between the terms "binding" and "association." The term "binding" is typically taken to refer to a short-term consequence of feature integration (e.g., Frings et al. 2020, for a recent review). However, it has become usual to refer to long-term bindings, which are essentially equivalent to associations (even though there might be a difference in "theoretical spirit," with binding approaches typically being based on "episodic," exemplar-based memory approaches rather than associative memory approaches).

Dreisbach et al. 2007; Forrest et al. 2014, for further arguments against a pure compound retrieval account; see Jost et al. 2013, for a review).

Note that all studies using 2:1 cue to task mappings observed faster responses for task repetitions with cue repetitions than for task repetitions with cue switches. This advantage of cue repetitions when repeating the task is taken as evidence for the retrieval of task sets that is facilitated if the same cue retrieves the same task set (Mayr and Kliegl 2003; see also Kandalowski et al. 2019) or for the retrieval of responses based on cue-stimulus-compounds (Logan and Bundesen 2003). (We will come back to these different accounts in Sect. 5 "models of task switching.") Irrespective of the exact mechanisms, the cue repetition advantage shows that large parts of task-switch costs result from task cue repetition benefits because the cue is associated with elements of the episode and retrieves these elements in case of cue repetitions. In the following, we will review studies that directly demonstrated that specific elements of the task processing episode are associated with each other and later on retrieved. We discuss cue-task, stimulus-task, and stimulus-category associations in this section before turning to associations with responses in the next section.

Gade and Koch (2007) provided direct evidence that cue-task associations are learned and retrieved when switching between tasks. In their study, participants first trained specific cue-task mappings for several hundred trials. Then the cue-task mappings changed in two ways. Either the cue-task mapping was reversed, or novel task cues were used to instruct the respective tasks. The reversal of the cue-task mapping resulted in longer RTs, especially in task switch trials. This result indicates that the task cues retrieved the task sets to which they were associated during training, and this associative activation interfered with the implementation of the new task set in switch trials.

In addition to task cues, also a stimulus that is processed in a specific task context is associated with this task and later retrieves the corresponding task set when being presented again. This finding of "item-specific" priming of task sets was first demonstrated by Waszak et al. (2003). In their study, participants switched between the tasks to read a word or to name a picture. Stimuli were line drawings superimposed by words, and some of these stimuli were presented in only one of the tasks, whereas other stimuli were presented in both tasks. Switch costs were much larger for stimuli that were presented in both tasks even if the occurrence in the other task happened more than 100 trials earlier. Waszak and colleagues took this as evidence that, in case of weak task-set activation, stimuli themselves trigger the task set to which they were associated before. Further evidence for this assumption revealed a study of Koch and Allport (2006) who assessed item-specific task priming effects in conditions with short or long cue stimulus intervals (CSI). The CSI manipulation was included in order to vary the amount of task-set activation before the target stimulus was presented. The item-specific task priming effects were markedly reduced with long CSIs, thus supporting the assumption that stimuli prime task sets especially in case of weak task-set activation (see also Rubin and Koch 2006, for a similar finding when an irrelevant context stimulus primes the frequently co-occurring task set). Moreover, Koch and Allport (2006) found that item-task associations had strong effects even with congruent target stimuli, for which the response is the same regardless of the task. This suggests that item-specific priming refers mainly to the task rather than to the response.

Yet, the impact of stimulus associations might not be limited to situations with weak task activation. Kiesel et al. (2007) assessed the impact of stimulus associations in task switch and task repetitions trials. In their study, participants categorized digits according to magnitude or parity. Half of the stimuli never occurred in the alternative task, whereas the other half of the stimuli occurred frequently in the other tasks. Like in the study of Waszak and colleagues (2003), switch costs were larger for stimuli presented in both tasks rather than in only one of the tasks. That is, performance was not only hampered for stimuli that occurred frequently in the other task in switch trials, but performance was also facilitated for these “frequent” stimuli in repetition trials. Thus, stimuli that are frequently paired with a specific task might trigger this task or parts of this task also in case of stronger task-set activation in task repetition trials. However, whether the impact of stimulus associations is actually due to stimulus-triggered associations with task sets or to associations with the respectively required response, like assumed by Meiran and Kessler (2008), cannot be differentiated in these experimental settings.

Such a differentiation requires an experimental setting that can distinguish task set and response set priming. Unfortunately, however, this differentiation is not trivial because we usually assume that task sets involve the mapping of stimulus to responses. Yet, there are some recent studies investigating item-specific priming effects that distinguish stimulus-classification and stimulus-action associations (e.g., Horner and Henson 2009; Moutsopoulou et al. 2015). Moutsopoulou and colleagues (2015) used line drawings of objects that were categorized either regarding size (smaller or larger than a shoe box) or regarding whether the depicted objects is mechanical (i.e., contains some mechanism like a motor, etc.) or not. The task cues indicated the currently required categorization and the required response. For example, the task cue “S + L” indicates that participants shall categorize the object as “small” or “large” by pressing the left key for small and the right key for large, while the task cue “L + S” instructs the same categorization but the alternative response. For one specific item (one specific line drawing), the category can repeat or switch, and the response can repeat or switch between prime and probe. Both types of repetitions, category repetitions and response repetitions, led to faster responses indicating that the item was associated with the respective category and the respective action.

Interestingly, these associations are rather long lasting, so that traces of item-specific priming effects are observed even in case of a 1-week interval between prime and probe (Moutsopoulou et al. 2019). Moreover, these associations built up fast: A single prime instance suffices for items to become associated with the respective category and action (Pfeuffer, Moutsopoulou, et al. 2018). Further, participants do not actually have to perform the task but presenting the category and the response as words conjointly with the items is already sufficient to induce item-specific category and response priming (Pfeuffer et al. 2017, 2018; see Longman et al. 2020, for a similar finding). It should be noted though that, unlike studies that introduced fixed contingencies between stimuli and tasks (e.g., Koch and Allport 2006; Waszak et al. 2003), not all studies that examined episodic repetition effects found that these contributed to switch costs. For example, Graham and Lavric (2021) found that performance was generally better when a specific stimulus item was processed on its next occurrence in the context of the same task again compared to a different task. And this episodic repetition benefit was not stronger on switch trials than on repetition trials and thus did not contribute to the size of switch costs (just as in Koch and Allport 2006, when there was a long preparation time). Thus, while the general episodic repetition benefit seems undisputable, the specific contribution to switch costs may depend on methodological details that require further exploration.

Taken together, there is evidence that retrieval effects induce interference in task switching. Thereby, different parts of an episode get bound and might be later retrieved, so that repetitions of task cues, task cue to task mappings, repetitions of stimuli, and their associations with task sets, task categories, and responses can induce interference in task switching. In addition, also response-repetition effects cause interference as will be discussed in the next section.

4.5 Contribution of Bindings in Task Switching: II. Effects of Response Repetition

The potential contribution of binding effects has also been discussed with reference to response-repetition effects in task switching. Already Rogers and Monsell (1995) observed that the common benefit of repeating a response is only observed when the task repeats but almost always turns into a cost when the task changes (see also Kleinsorge and Heuer 1999). This pattern is stable across stimulus modality (e.g., Quinlan 1999; Seibold et al. 2019, for demonstrations of such effects with auditory target stimuli) and response modality (e.g., Schuch and Koch 2004, for response repetition effects across manual and vocal responses). Generally, there are two classes of accounts for this pattern of response-repetition effects, which we broadly label as binding accounts and response inhibition accounts.

The response inhibition account assumes that situations that require frequent task switching go along with a bias to change the response when the task changes, too (see Grzyb and Hübner 2013). This inhibition of the previously produced response can be measured in task-switch trials as a response-repetition cost. Theoretically, this cost should also be present in task repetitions, but here this cost is overcompensated by a larger benefit of repeating the same task and category (or even the exact target stimulus itself), so that these trials have a net benefit based on the mixture of a cost due to response inhibition that is masked by positive category priming in task repetitions (Druey and Hübner 2008). The contribution of inhibition of previous responses in task switching has been supported by several studies (e.g., Grzyb and Hübner 2013; Koch, Schuch et al. 2011).

In comparison, the binding approach does not postulate a specific response inhibition mechanism but is based instead on more general principles of feature binding in action control (for reviews, see, e.g., Frings et al. 2020; Hommel 2004). The binding approach assumes that performing a task generates an episodic representation in memory that includes the features of the trial, such as the cue, the target, the response, and possibly also a higher-level representation of the task itself (the task set) and even task-irrelevant aspects like contextual stimuli. The more of such features are repeated from one trial to the next, the more performance will benefit from episodic retrieval, which will thus produce a repetition benefit. In a task switch, in which no feature repeats, there is simply no retrieval benefit. However, in situations in which some features repeat but other features change, the repeated features will retrieve the previously bound (or associated) features as well, resulting in a partial mismatch in retrieval. This partial mismatch generates interference because the mismatching features need to be "unbound" and replaced with the correct features. That is, the relative cost of response switches in task repetitions as well as the relative cost of response repetitions in task switches can be explained as "partial repetition costs" (Frings et al. 2020), suggesting a strong role of episodic binding in the pattern of response repetition effects in task switching. Variations of such a binding account were proposed by Meiran (2000), who argued that responses require recoding if repeating the same response has to change its "meaning" in the context of a task switch. In addition, Schuch and Koch (2004, 2006) suggested a process of associative strengthening for the binding of task and response that would create interference when the previously strengthened association now competes with the new task-specific response mapping. In a similar vein, Altmann (2011) suggested that all episodic features sum up in terms of sequential matches vs. mismatches and the net effect determines the performance level (see also Schmidt et al. 2020, for a neural network model of episodic feature retrieval in task switching).

So far, there is supporting evidence both for the response inhibition account and the binding account, so that these accounts co-exist. Recently, Koch et al. (2018) argued that the inhibition of the previous response is not necessarily mutually exclusive with binding processes but that they might complement each other, suggesting a "hybrid" account including both mechanisms. In this study, Koch et al. (2018) introduced visual and auditory cues (high vs. low bars visually presented on the screen and high vs. low tones presented via loudspeakers), while the tasks were only instructed by the feature "high" vs. "low," so that the modality of the cue was a task-irrelevant feature. Nevertheless, the task repetition benefit (i.e., switch costs) was generally larger if the cue modality repeated as well, suggesting that the task repetition benefit depends on episodic similarity across trials (see also Kandalowski et al. 2019, who replicated this finding and extended it to task-irrelevant variations of target modality). Further, also the response repetition benefit was larger when the cue modality repeated. In contrast, when the task switched, the influence of variation in cue modality was minimal, suggesting that it is primarily the response repetition benefit that is affected by similarity across trials, whereas the response-repetition cost might be due to persisting inhibition of the previous response that is unaffected by retrieval.

In sum, the pattern of response-repetition effects in task switching presumably requires a complex explanation that is based on more than a single mechanism. Irrespective of the exact mechanisms underlying response repetition effects, we have seen that the general principle of binding and retrieval can account for a good part of the empirical findings and thus represents a viable framework for explaining interference effects in task switching (see Frings et al. 2020).

4.6 Modality-Specific Effects in Task Switching

We have mentioned that variations of cue modality and target modality can influence the pattern of repetition effects in task switching (see Kandalowski et al. 2019; Koch et al. 2018). In these studies, the variation of modality referred to a task-irrelevant feature. Overall, however, most studies interested in task switching used visual stimuli (and cues) and manual responses and did not vary modality-specific variables. There are a few studies though that used auditory stimuli (e.g., Lukas et al. 2014; Quinlan 1999; Seibold et al. 2019), and some studies used vocal responses (e.g., Yeung and Monsell 2003). Yet, such studies did not systematically explore modality effects but had different theoretical aims. In addition, because of specifics of the sensory systems, it is not easy to compare performance across visual and auditory stimulus processing directly (e.g., it would require psychophysical matching of stimulus intensity, and it would need to take into account the inherent sequential nature of auditory stimuli, so that RT to visual and auditory stimuli are difficult to compare). Likewise, it is difficult to compare RT with manual and vocal responses directly because the measurement of RT onset with vocal responses might be slightly delayed and depend on item-specific factors much less than typical key press responses.

A systematic exploration of modality-specific effects that avoids these psychophysical difficulties has been started by Stephan and Koch (2010, 2011). They combined manipulations of stimulus modality (e.g., visual vs. auditory) with manipulations of response modality (e.g., manual vs. vocal) in order to create tasks based on different modality mappings. For example, Stephan and Koch (2010) had participants switch either between visual-manual (VM) and auditory-vocal (AV) tasks or between visual-vocal (VV) and auditory-manual (AM) tasks. They used spatial discrimination tasks with left vs. right stimuli (i.e., visual stimuli presented left vs. right on the screen or auditory tones presented to left vs. right ear), which required either left vs. right key press responses or “left” vs. “right” vocal responses, so that there was high spatial S-R compatibility throughout all tasks and mappings.

Based on the theoretical notion of ideomotor theory, which assumes that response selection includes an anticipation of the sensory consequences of the response (e.g., Greenwald 1972), Stephan and Koch (2010, 2011) defined modality compatibility. Specifically, they argued that an AV task is modality compatible because vocal responses usually generate auditory effects (such as when speaking or singing) instead of visual effects, whereas in VM tasks, manual responses produce visual effects (such as in eye-hand coordination) more often than they produce auditory effects (which may, of course, still be relevant, such as in piano playing). Therefore, AV tasks and VM tasks represent modality mappings that were termed modality compatible, relative to the VV und AM mappings. The two latter tasks are, relatively speaking, less modality compatible (e.g., vocal responses rarely result in immediate visual effects), so that, for simplicity, they can be called modality incompatible.[2]

Stephan and Koch (2010) found that switch costs were smaller when switching between two modality compatible mappings than when switching between two modality incompatible mappings. Note that in both AV-VM and AM-VV combinations, there are visual and auditory stimuli as well as manual and vocal responses, so that averaging across the two mappings in each modality compatibility condition equates all the abovementioned psychophysical differences across the experimental conditions. Hence, the finding of reduced switch costs cannot be due to "simple" sensory or motor effects as these should be the same across modality conditions. Recently, Friedgen et al. (2020) argued that switching between modality incompatible mappings creates additional interference because selecting the response activates the anticipation of response effects in a modality that actually refers to the competing task and thus increases task competition in modality-incompatible tasks (e.g., in VV task, the vocal response activates an anticipation of auditory effects which in turn primes the competing VM task).

Such modality compatibility effects in task switching can be demonstrated with other pairs of stimulus modalities (e.g., Stephan and Koch 2015, found that the effect on switch costs was even enlarged when using tactile stimuli instead of visual stimuli) and with other pairs of response modality (e.g., Stephan et al. 2021, found that the influence of modality compatibility is still present if manual responses are replaced with pedal responses). Moreover, there are also some theoretically relevant boundary conditions for this effect to occur. For example, Stephan et al. (2013) found that modality compatibility effects do not occur with oculomotor responses, presumably because oculomotor responses are part of the orienting reflex which responds to visual and auditory stimuli alike.[3] Also, Fintor et al. (2018) demonstrated that the benefit of modality compatibility really lies in the combination of two modality compatible tasks, whereas "mixed" compatibility mappings (i.e., one compatible and the other incompatible) do not produce any benefit of modality compatibility per se at the level of the individual tasks. This suggests that the effects of modality compatibility are not due to differences in difficulty of individual mappings but rather represent an emerging feature of mapping combinations in task switching and thus a task competition phenomenon (see Friedgen et al. 2020).

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[2] Note that Greenwald (1972) defined ideomotor compatibility in a narrower sense in terms of identity of stimulus and anticipated sensory response effect. That is, hearing "One" and saying ONE would be ideomotor compatible and modality compatible, whereas hearing "One" and saying TWO would no longer be ideomotor compatible but still preserves modality compatibility in terms of the match of stimulus modality and modality of the sensory response effects (both auditory).

[3] For analogous findings in the PRP paradigm, see Janczyk et al. (2014).

Beyond task switching research, such modality-specific effects have also been reported in dual-task research (Hazeltine et al. 2006; Schacherer and Hazeltine 2020; Wirth et al. 2020), showing reduced dual-task costs when combining two modality-compatible tasks relative to two modality-incompatible tasks. This suggests a general effect of mapping compatibility that extends across the specifics of the task-switching paradigm and thus represents a general challenge for current models of task switching (and multitasking) because these models do not take into account such modality-specific difference in processing and in task competition.

4.7 Summary

We have seen that performance in task switching is affected by a variety of factors that influence between-task interference and that suggest a strong contribution of persisting activation and inhibition of competing task sets. In addition, there are also interference effects based more specifically on item- or response-specific bindings, and there are also modality-specific factors that influence performance. Note that these interference effects are based on target processing, so that the processes underlying resolution of such interference can thus be classified as "reactive" control processes. This focus on reactive control is complementary to the focus on proactive control, which denotes those control processes that can be instigated prior to target onset in order to optimize the preparatory state for the next task. To explain the interaction of reactive and proactive control processes is a major goal of models of task switching, which would need to take into account the various interference effects described so far. In the next section, we turn to theoretical models of task switching.

5 Theoretical Accounts and Models of Task Switching

When considering performance in task switching, the most important empirical phenomenon is the robust performance costs when switching the task relative to repeating it, that is, the switch costs. Theoretical models differ fundamentally in their assumptions about what the empirically observed switch costs actually measure. The simplest idea would be that the switch costs measure the amount of time that a willful, voluntary, endogenous, proactive act of control needs in order to shift the task set. This act of control has often been termed "reconfiguration" (Meiran 1996; Rogers and Monsell 1995).

However, because many interference effects seem to defy the idea that switch costs represent a "pure" measure of proactive control in the sense of reconfiguration, Rogers and Monsell (1995) have argued that there are components of switch costs that are actually due to stimulus-triggered, reactive control processes that do not take place prior to target onset. We have described such stimulus-triggered processes in terms of persisting activation or inhibition of task sets as well as in terms of involuntary task-set reactivation based on item-specific bindings. Importantly though, it has also been assumed that switch costs do not represent an act of proactive control at all (Logan and Bundesen 2003) and that switch costs can be explained completely based on accounts that are rooted in the dynamics of memory encoding, maintenance, and retrieval in general (for review and discussion, see Grange and Houghton 2014; Schmidt et al. 2020). In this section, we give an overview of those accounts. Different models focus either on one of the three main ideas or implement combinations of these ideas. We start with simple accounts and proceed to more complex accounts.

5.1 Task Set Inertia (TSI): Costs of Overcoming Involuntary Aftereffects (Positive and Negative Priming)

The question as to whether task switching requires an "executive" control process that is only required on task switch trials but not on task repetition trials (Rogers and Monsell 1995) has inspired a fruitful theoretical debate. One early, prominent model assumed that switch costs do not reflect the process of task-set control directly but that they simply reflect the persisting aftereffects of having performed tasks previously and thus of having previously activated a task set (Allport et al. 1994). Note that this account assumes that there are acts of task-set control, but switch costs do not measure them directly. Specifically, Allport et al. (1994) proposed that switch costs are mainly due to proactive interference at the level of task sets, so that the persistence of a task set in memory renders it harder to select, retrieve, and implement a new task set. They termed this notion "task set inertia" (TSI). The notion of TSI implies that there is repetition priming when repeating a task, and this repetition priming actually produces interference when a task switch is required. Hence, in view of the TSI account, it is fair to say that the switch costs, in addition to interference that occurs on task-switch trials, also represent a repetition benefit in task repetition trials that is not available in task switches. This account can explain switch costs without assuming that a specific component of the switch costs represents the extra time needed to reconfigure the task set.

Note that Allport and Wylie (2000) argued that TSI can also take the form of persisting inhibition of the currently irrelevant task set, which renders its reactivation in a task switch harder. This notion of "negative priming" at the level of task sets has found empirical support in work on task inhibition using n-2 task repetition costs (see Grange et al. 2013; Sexton and Cooper 2017, for models). However, most models are based on activation only. One such model was proposed by Gilbert and Shallice (2002). In their neural network model of task switching with Stroop color-word stimuli, there are two processing pathways, one for color naming and one for word reading. These pathways consist of sets of interconnected stimulus units and response units. Importantly, the activation along these pathways is biased by the output of task nodes to make sure that the correct task is performed. Because this bias persists, it takes longer to select a response when the task switches and thus when the previous bias needs to be overcome based on the present task. This implements the idea of task repetition priming in a straightforward way. Moreover, the model also includes a short-term loop that binds the current stimulus to the actual task, so that this model is able to explain the influence of item-specific stimulus-task bindings, but this is restricted to the immediately preceding trial. Note that this model is agnostic with respect to inhibition, assuming that competitive activation in the network leads to mutual suppression, so that no explicit inhibitory mechanism is included. However, it would be possible to recast such activation-based models in terms of inhibition (Yeung and Monsell 2003). Most importantly, in the model proposed by Gilbert and Shallice (2002), there is no *switch-specific* task-set reconfiguration process because the processes required in switch trials and in repetition trials are essentially the same, but they simply take a bit longer on switch trials (because of the bias for the other task), thus explaining the switch costs.

5.2 Episodic Retrieval Model

The very notion of TSI implies that task-set activation or inhibition persists in memory. A slightly different theoretical approach is to assume that task sets need to be retrieved from memory and that the dynamics of task retrieval, referring to initial activation and subsequent decay, produces task switch costs. Altmann and Gray (2008) presented a computational model based on the production system architecture ACT-R (Anderson et al. 2004). They assumed that a task cue leads to the encoding of a task code that needs to be maintained in memory. Task performance is guided by the most recently encoded task code. However, because in task switching studies many such task codes have been encoded before, there is increasing interference in memory, so that it is hard to discriminate the currently relevant task code from earlier, irrelevant task codes. Moreover, the activation of task codes decays passively over time, so that with increasing number of trials of the same task, the relevant task code will be less discriminable (i.e., the difference in activation of the current task code and earlier task codes will gradually decrease), so that performance will gradually get worse across extended runs of the same task. If a new run starts, a new cue will generate a new task code, which is slightly easier if this cue is the same as before than if the cue refers to the other task. Using this model, the authors can explain the basic switch costs, and they can explain a specific empirical effect in uncued runs of tasks, the so-called within-run slowing (Altmann 2002; Altmann and Gray 2002). Again, in this model, there is no principled difference in the processes required in task switches and task repetitions, and the switch costs derived from priming of earlier task codes.

A somewhat similar idea is represented in the mathematical model proposed by Schneider and Logan (2005). This model is based on earlier modeling of empirical data in the 2:1 cue-to-task mapping procedure (Logan and Bundesen 2003).

Essentially, the model assumes that task performance in task switching is mainly based on learning cue-target compounds, which can jointly retrieve the correct response from memory. These authors argue that this is what happens in task switch trials and task repetition trials alike, so that there is no extra switch-specific task-set reconfiguration process needed. Switch costs occur in this model because the cue component of the cue-target compound is primed in a task repetition trial, so that it is encoded more quickly in a task repetition than in a task switch trial. This explains the switch costs in terms of a cue repetition benefit. Moreover, this model can also easily explain effects of preparation time, because with more time for cue encoding, the cue is already encoded when the target is presented, so that only the target needs to be encoded and compounded with the cue to retrieve the response.[4] Put differently, with short cuing interval, performance includes time for cue encoding that is no longer needed when the preparation time is long. Notably though, the cue repetition benefit should be much smaller or even abolished when an alternative cue for the same task is presented. This model has inspired a considerable debate about the empirical dissociation of cue switch costs (or repetition benefits) and task repetition priming (see Jost et al. 2013, for a review). Importantly, in its strongest version, this model does not require any extra control process and is simply built on the memory dynamics of cue-compound retrieval. The cue-compound idea has been generalized in so-called episodic feature binding models, to which we turn next.

5.3 Episodic Feature Binding Models

Empirical findings suggesting a strong contribution of item-specific binding effects in task switching (e.g., Koch et al. 2005; Waszak et al. 2003) inspired Altmann (2011) to propose an episodic retrieval model of task switching. This model is in the spirit of the "event file" approach (Hommel et al. 2001), which assumes that stimuli and responses are encoded in terms of their discriminable features (e.g., location and color for stimuli or effector and response location for responses). Performance is generally supposed to be a function of the similarity of the current task episode to the previous task episode, and re-appearance of a feature tends to retrieve the associated features, that is, to re-activate previous feature bindings (see Frings et al. 2020, for a recent summary and review). The more features are repeated from one trial to the next, the more similar are the episodes, and the better is performance. Based on this feature binding approach, Altmann (2011) proposed a model in which each variable feature that could repeat or switch produces "episodic points" that are summed up in order to predict the net benefit of priming based on retrieval.

In light of this numerical model that simply sums up the benefits of individual feature repetitions, Schmidt et al. (2020) recently proposed a much more complex

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[4] Please note, however, that the model is agnostic regarding residual switch costs. If the preparation time is sufficiently long so that cue encoding can be completed before the target stimulus is presented, the model does not predict switch costs.

neural network model of task switching based on the parallel episodic processing model (Schmidt et al. 2016). Their model also includes goal (or "task") nodes, like the model of Gilbert and Shallice (2002), but it can explain a much wider variety of repetition effects in task switching. In fact, the authors argue that their model can explain task switching without assuming any active cognitive control because all what the model does in a task repetition trial is to retrieve features from memory, and this is not any different in a task switch. Interestingly, the authors discuss at greater length whether some of their interactive processes, most notably with respect to residual goal node priming, actually implements mechanistically what other researchers have called a "task set," which is essentially a control representation. Notwithstanding these conceptual and terminological intricacies, the important point is that the Schmidt et al. (2020) model is entirely based on the principle of feature binding and retrieval, and the authors consequently argue that there is nothing like an "executive" control process required that "reconfigures" the task set. It should be noted though that the authors did not attempt to model the preparation-based reduction of switch costs, which is typically seen as the most relevant finding in the discussion of "executive" control and task-set reconfiguration, so that it is not clear how their model could accommodate this finding.

Episodic models of task switching are typically cast in the spirit of parsimony (even though it is not always easy to quantify the degrees of parsimony across models), assuming that no executive "deus ex machina" is required to explain switch costs because these costs emerge naturally from the dynamics of the system. However, much of the fascination in task switching derives from the idea that the costs of task switching are related to an endogenous act of control, such as "task-set reconfiguration," that is not determined exogenously by the stimulus itself but rather by some internal intention or goal, which can be voluntarily shifted. (The discussion of the philosophical implications of this exogenous-endogenous dualism is beyond the scope of this chapter.) Given the clear evidence for the stimulus-based interference effects, several dual-mechanism models have been proposed to combine both exogenous and endogenous components.

5.4 Two-Mechanism Models I: Reconfiguration and TSI

Early theoretical accounts proposed two separate control processes when switching from one task to the other. For example, Rogers and Monsell (1995) assumed that a stage-like task-set reconfiguration is required that could be carried out partly in advance, prior to the onset of the target stimuli as an endogenous preparation process. Similarly, Logan and Gordon (2001) designed an "executive control" model for dual-task performance, where the shift from one task to another in a dual-task trial requires an executive control process (i.e., transmission of new task-specific parameters for stimulus selection in a visual attention module). Note that even though this model was explicitly designed for dual-task processing, it still represents a model for task-set control. However, to our knowledge, it has not yet been applied to explain effects in the task-switching paradigm.

However, in task switching, there is the finding that "residual" switch costs can be usually observed even at very long preparation intervals. Based on this finding, Rogers and Monsell (1995) assumed that some of the reconfiguration can only be completed with the onset of the target itself, so it has to be triggered exogenously by the target stimuli. Consequently, a task switch cannot (or at least is not) be completely prepared, explaining the residual costs. This two-stage logic is also part of other models, such as that proposed by Mayr and Kliegl (2003), who suggest a separation of task selection and task implementation, or Rubinstein et al. (2001), who distinguish goal shifting and rule implementation (see Yeung and Monsell 2003, for a model assuming more gradual instead of all-or-none reconfiguration). Furthermore, the idea that there is some kind of cue-based goal setting, which can benefit from long preparation time, that interacts with generic task-set priming (i.e., TSI) and item-specific feature binding effects, has been proposed by Koch and Allport (2006).

Some of these ideas have also been implemented in formal models. For example, Sohn and Anderson (2001) proposed a production-system model of task switching, in which performance in task switching is guided by both executive and automatic control. The model assumes that there are previously learnt productions in procedural memory (e.g., "encode task"), which are controlled by chunks in declarative memory. Automatic control is based on the current stimuli and the previous memory representations and essentially produces switch costs in terms of lack of repetition benefits from positive priming. However, there is also an executive control process that can intervene when the upcoming task is predictable and when there is enough time for advance preparation (i.e., activating a "prepare-switch" production). In their model, the probability that the prepare-switch production will be selected increases with increasing preparation time, whereas it will not be activated in advance when the upcoming task is not yet predictable.

A different model assuming two very different processes, or control representations that can be reconfigured, was proposed by Meiran (2000). He distinguished between a stimulus set, which functions to filter the stimulus input according to the current task demands (thus a form of selective attention), and a response set, which reflects the previous association of the response and the task category that it is meant to indicate (e.g., left key indicates "odd" rather than "smaller than 5"). In that model, the stimulus set can be reconfigured in advance, in the sense of increasing attentional weight to task-relevant stimulus features or dimensions, producing preparation benefits. In comparison, the response set basically reflects the aftereffect of previous task performance and thus represent something very similar to TSI. It is the persisting setting of the response set that is responsible for residual switch costs in this model. In that model, the response set is reconfigured retroactively, that is, only after the response has already been performed, so that it always represents a response set that is biased to the previous task, favoring task repetitions but producing interference in case of task switches.

In a later update of this model, Meiran et al. (2008) renamed the two control representations as input set and action set. This model is much more flexible than the earlier model. It suggests that with short preparation time, the model is configured to filter the input to make sure that the correct input information is encoded. However, with long preparation time, it is also possible to reconfigure the action set (unlike in Meiran 2000), so that the response categories themselves are already preactivated. This highly flexible model can reproduce a variety of empirical phenomena in task switching (see Schmidt et al. 2020, for a recent discussion).

Finally, there is also a neural network model that assumes two extra control processes. This model, proposed by Brown et al. (2007), is to some degree structurally similar to the model of Gilbert and Shallice (2002), but unlike that model, the Brown et al. model (2007) includes two explicit control modules that detect two different types of conflict. One is an "incongruency detector" that monitors the degree of response conflict that the current stimulus evokes in the system. This incongruency detector is inspired by Botvinick et al.'s (2001) conflict monitoring model. Moreover, there is an additional explicit control module, the "change detector." This module monitors task conflict, which occurs when the task has changed, and it also detects response changes. In case of response switches, this model would essentially reduce (inhibit) activation in the response units (possibly similar to the response inhibition account proposed by Hübner and colleagues, e.g., Druey and Hübner 2008). Inclusion of these two control modules renders the model fairly complex. This model is designed to account for various sequential adjustments of control settings. However, this model was not designed to account for more specific feature repetition effects, even though it seems plausible that it could be expanded to do so in a future version of the model. Likewise, a neural network model of high complexity has also been proposed by Herd et al. (2014). A particular focus of that model was to relate the various modules in the network model neuropsychologically to brain structures (e.g., prefrontal cortex, basal ganglia) and functions (e.g., working memory updating) in order to specifically model interindividual differences in a biologically plausible way. A more detailed description of this model is beyond the scope of this chapter.

5.5 Two-Mechanism Models II: Goal Setting and Goal Inhibition

In the preceding subsection, we have already mentioned that neural network models incorporate some inhibitory mechanisms. Specifically, most models assume that activation is competitive in the system, so that concurrently activated representations mutually inhibit each other to some degree. Thus, inhibition is "inherent" in the model. However, there are also accounts that assume that inhibition is an extra control process. These accounts typically assume that there is an active process of goal selection (or task activation), typically triggered by an explicit task cue. The actual selection and implementation of the task set goes along with inhibition of the preceding, now competing task set. This "backward inhibition" mechanism (Mayr and Keele 2000) has been derived from the empirical finding of n-2 task repetition costs (for reviews see, e.g., Gade et al. 2014; Koch et al. 2010), as described in an earlier section.

The proposed active control process (task activation) and the assumed task inhibition process are most likely separate. For example, many studies found that variations of the CTI produce substantial general preparation benefits in overall performance but have only very small or at best modest effects on n-2 repetition costs (Mayr and Keele 2000; Schuch and Koch 2003), and the conditions under which preparation actually affects task inhibition are still under debate (Gade and Koch 2014; Scheil and Kleinsorge 2014). In contrast, there is evidence that n-2 task repetition costs depend reactively on the degree of conflict in the preceding trial. For example, Gade and Koch (2005) manipulated the RCI (while keeping the CTI short) and found that n-2 repetition costs increased with decreasing RCI. They proposed that this finding indicates that with long RCI, there is some decay of the preceding task set, so that it produces less task conflict in a subsequent task switch, which in turn requires less "backward inhibition" of the preceding task set.

The previously described models were not designed to model this kind of task inhibition. In fact, because the described models are all essentially activation-based, there does not seem much room for additional inhibitory connections. More recently, two models have been developed to account for n-2 repetitions costs (Grange et al. 2013; Sexton and Cooper 2017). Grange et al. (2013) used a production system architecture and applied a short-term inhibitory component, making it a bit harder to activate a new chunk referring to the translation of a new cue into a new task representation. This way, n-2 repetition costs could be explicitly modeled. However, this essentially represents a "self-inhibition" mechanism, whereas there is evidence that it is the process of activating the new task set that triggers inhibition of the competing task set (Schuch and Koch 2003). Thus, while this model represents a first step toward explicitly modeling task inhibition, this model is still not geared toward explaining the full range of inhibitory phenomena in task switching (see Grange and Houghton 2014, for a discussion). In comparison, the model proposed by Sexton and Cooper (2017) is a neural network model in the tradition of the Gilbert and Shallice (2002) model, but it includes an explicit task conflict monitor mechanism (like the Brown et al. 2007, model). When a task node is activated, this activation persists over time (producing TSI and thus repetition priming, or switch costs), but because of this activation persistence, when a new task node is activated, the task conflict monitor detects two active task nodes, and then both task nodes receive an inhibitory control input, and this inhibition is carried over to the next trials and decays only gradually. Therefore, after switching from one task (A) to the next (B), it is harder to switch back (ABA) than to switch to a third task (CBA), which essentially corresponds to the finding of n-2 repetition costs.

Notably, these two models can explain basic inhibitory effects at the task level, one referring to self-inhibition of the just executed task (Grange et al. 2013) and the other to conflict-driven inhibition of competing tasks (Sexton and Cooper 2017), as it was proposed by Koch et al. (2010; see also Schuch et al. 2019, for a recent discussion of such conflict-control loops). However, it should be noted that these models were not designed to account for interference effects at the level of feature retrieval, so that, despite their impressive feats, these models remain incomplete in that regard.

5.6 Summary

In this section, we have described a number of formal models that have implemented ideas coming from verbally stated theoretical accounts. Some models are rather parsimonious and try to model performance based on general principles of learning and memory, but other models explicitly implement two-stage accounts or even more complex accounts. At this point, it seems as if no current model is able to account for the full complexity of task switching, even though they are very useful in formalizing and thus clarifying the processing assumptions inherent in verbal and sometimes slightly imprecisely stated earlier theoretical accounts. Generally, while all models basically can account for repetition priming, which in turn produce costs for a task switch and thus implement the basic TSI mechanism, the models differ in terms of how exactly they are realized (e.g., as mathematical model, as production system model, or as neural network model). Moreover, while some models attempt to model preparation effects to see how top-down processes can affect switch costs, other models focus more on bottom-up effects, for example, based on feature bindings (see Schmidt et al. 2020, for a recent neural network model and discussion of alternative models). A model that could potentially integrate some of the top-down and bottom-up effects in a novel way was proposed by Oberauer et al. (2013). This model differentiates between declarative working memory, holding the current content of thought, and “procedural working memory,” which holds higher-order representations, such as task sets, that govern how declarative content is processed. By virtue of being an associative memory model, it incorporates attentional mechanisms in stimulus selection embedded in a matrix of bindings of recent elements. This enables the model to account for a variety of basic phenomena in task switching, and it also allows for including episodic bindings. Currently, it is probably not possible to determine which is the “best” model because all models have different merits. Probably it would be overoptimistic to assume that any model will be able to fully capture the complexity of human behavior in task switching situations. Future modeling work will be required to integrate the existing work in order to improve our understanding of task switching to a degree that it still represents a useful abstraction that can be generalized.

6 Gender-Related Differences in Task Switching

When describing the basic experimental paradigms, empirical effects, theoretical accounts, and formal models of task switching, the focus was on the general cognitive processes underlying task-switching performance. However, there is no doubt that human performance in task switching is subject to quite substantial variability both within and across participants, that is, there are substantial interindividual differences in performance. This raises the issue of whether there are certain people who are particularly proficient in multitasking generally and in task switching particularly.

For example, it has been suggested that bilinguals, by virtue of extensive daily training of inhibitory control of the competing language, are also better at inhibiting competing tasks and thus also perform better in task switching. The evidence for this bilingual advantage appears to be rather mixed (e.g., Antoniou 2019, for a review), and we do not go into further detail as this topic is also covered in this handbook by Wiseheart (Chap. 12, this volume). As another example, Watson and Strayer (Watson and Strayer 2010, see also Strayer et al. Chap. 10, this volume) reported that there is a very small group of individuals who is able to perform in multitasking without any costs relative to single-task situations (even though this behavioral advantage seems rather elusive, see Medeiros-Ward et al. 2015). Here we would like to briefly touch upon a popular topic in slightly more detail, and this refers to the often assumed advantage of women over men in multitasking.

According to a popular belief, women outperform men in multitasking (Szameitat et al. 2015). Several studies have examined this issue using variants of dual-task paradigms (e.g., Mäntylää 2013), but generally the results of such studies have been fairly mixed (see Hirsch et al. 2019, for a brief summary). Consistent with the focus of the present chapter on task switching, we focus on those studies that actually examined measures of switch costs or mixing costs in task switching. There are very few such studies.

In one study, Stoet and colleagues (2013) asked large groups of female and male participants to either repeat or switch between a shape discrimination task and a filling discrimination task, and the authors also included single-task conditions. However, they did not find a significant difference in switch costs for female vs. male participants. Yet, for mixing costs (i.e., mixed-task vs. single-task performance), they found that men showed approx. 10% more mixing costs than women (336 ms vs. 302 ms). However, when the authors created more "real-life" switching scenarios in their second study, they could no longer find a gender difference. Moreover, in an fMRI study, Kapustova et al. (2015) compared performance in a block of trials requiring switching between a shape classification task and a number classification task with performance in a control condition (note that this control condition was not very comparable to the switching condition as it included a different task). However, they did not find any gender-related differences in the performance cost of task switching. Even though the authors found some significant switching-related differences in the pattern of brain activation across female and male participants, this study rather suggests that at least with regard to actual performance there is no obvious gender difference in task switching.

More recently, Hirsch et al. (2019) re-assessed the evidence (for both dual-task and task switching performance) and ran a study on switch costs and mixing costs. In addition to having reasonable statistical power (N = 2 × 48), this study also controlled for possible gender differences in relevant cognitive background variables, such as working memory, processing speed, spatial abilities, and fluid intelligence. The authors found no evidence for any gender-related difference in switch costs (neither in RT nor in error rates), but they also could not find any difference in mixing costs (thus not replicating the finding of Stoet et al. 2013), again neither in RT nor in error rates. To complete this picture, these authors also did not find any evidence for gender-related differences in several indices of concurrent multitasking in an otherwise comparable dual-task paradigm. In general, they found evidence that rather favors the null hypothesis (in terms of Bayes factors) of no gender-related differences, and hence the authors could not at all confirm the widespread stereotype of better multitasking abilities in women.

Given the reported evidence, which is mixed, and with more recent data challenging previous findings of gender-related differences in task switching, we can ask whether this stereotype is simply based on a myth. Yet, before such a strong general conclusion can be drawn from existing empirical data, it will be important to examine whether there might be gender-related differences in more specific tasks for which meta-analyses have already demonstrated gender-related differences in basic cognitive abilities (e.g., verbal tasks vs. spatial tasks; see, e.g., Voyer et al. 2017). Future research will be needed to examine this issue further.

7 Outlook

In this chapter, we have reviewed the current state of research in task switching. We have described the basic phenomena, the basic paradigms, and experimental methodology as well as theoretical accounts. Some of the accounts are stated verbally, while other accounts have been formalized in models. These models reflect the current state of knowledge about the interplay of proactive and reactive control processes.

One of the complexities of theorizing in task switching is that this interplay of proactive and reactive control processes may be more variable than is often assumed. For example, Goschke (2000; see also Mayr and Keele 2000) argued that there is a flexibility-stability dilemma in task switching, implying that those processes that optimize performance in task repetitions will include processes that shield the current task set from interference and thus giving stability in task performance. But exactly these processes hinder a switch of task if this is actually required by a situational change (e.g., with a new task cue), so that increased stability comes at a cost of decreased flexibility. Likewise, increasing flexibility will result in less shielding and more distractor-based interference, hampering performance in task repetitions.

Because it is exactly this balance that needs to be implemented in the control system to allow context-sensitive variability in the degree and type of control, it has been suggested that there might be *meta-control* processes guiding how much control is invested in task-set shielding, which in turn determines the ease of shifting task set and thus the degree of cognitive flexibility (Eppinger et al. 2021). Such meta-control processes may be related to the monitoring and control loops recently postulated for a variety of cognitive control situations, including task switching (see review by Schuch et al. 2019). We believe that this perspective on dynamic temporal fluctuation of control state will inspire future empirical and theoretical work on task switching to embed task switching performance in a larger motivational-volitional framework.

Likewise, while we focused our review on task switching, it is notable that there is also strong relation to dual-task research (see Fischer and Janczyk Chap. 1, this volume). There is good reason to assume that the theoretical commonalities, in terms of the underlying mechanisms, in task switching and dual-task performance are much larger than the methodological differences in research paradigm (see Koch et al. 2018, for an integrative review). In particular, we believe that work on practice and learning in task switching and in dual-task performance will converge, providing a better understanding of how people can adapt control processes to recurring multitasking requirements and thus show plasticity in the cognitive organization of task processes (see Karbach and Strobach Chap. 8, this volume; Strobach and Karbach 2021).

Moreover, we would like to emphasize that task switching is a powerful experimental methodology that can be used in more applied research areas as a valuable research tool. For example, in human factors research, multitasking and task interruptions are prevalent and can account for many interference effects in human performance (Hirsch et al. Chap. 4, this volume; see also Janssen et al. 2015, for an overview). Further, driving a car can be considered as a multitasking requirement, and additionally many drivers engage in other tasks while driving (see Strayer et al. Chap. 10, this volume).

Taken together, task switching represent more than just an experimental paradigm but is actually an empirical methodology and a theory-based research program, together with a rich set of empirical phenomena. Future progress can be expected if sequential task switching can be related more closely at the theoretical level with concurrent multitasking situations (Koch et al. 2018) but also with the study of interference in multitasking situation with clear task priorities, such as when a primary task needs to be resumed after having been interrupted by performing a secondary task. In fact, task interruption research has produced a different set of empirical phenomena whose theoretical accounts are not yet well enough integrated with accounts for task switching. Finally, in addition to the behavioral-functional level of description of task switching that we have taken here, we can also expect cognitive neuroscience to provide us with new research directions (see Brass and De Beane, Chap. 7, this volume). We could not cover this research here, but we believe that, for example, neuroscience work on meta control (Eppinger et al. 2021) will also inspire more cognitive-behavioral work and will thus foster scientific progress in the area of human multitasking in general.

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Task Interruptions

Patricia Hirsch, Iring Koch, and Tobias Grundgeiger

1 Introduction

Interruptions are widespread in both private and work environments. We are all familiar with those situations in which an activity is interrupted by another and has to be resumed later. For instance, while reading this chapter, one might be interrupted, to give only a few examples, by an incoming phone call, an urgent email notification, or a person asking a question.

The prevalence of task interruptions has been studied in several work environments, and it has been consistently shown that task interruptions occur multiple times within a day (e.g., Bellandi et al. 2018; Czerwinski et al. 2004; Sykes 2011). In the healthcare domain, for example, intensive-care-unit nurses have been observed to be interrupted almost 7 times per hour and emergency doctors nearly 11 times per hour, (Grundgeiger et al. 2010; see Grundgeiger and Sanderson 2009, for a review). Importantly, due to advances in technology and telecommunications, the prevalence of task interruptions is expected to increase further in numerous work-related environments in the future (e.g., Hopp-Levine et al. 2006).

Generally, task interruptions lead to a deterioration in well-being and to a performance decline in the interrupted task (see, e.g., Couffe and Michael 2017; Trafton and Monk 2007; Werner et al. 2015, for reviews). More specifically, at the emotional level, task interruptions are accompanied by an increase in negative emotions such as annoyance, anxiety, frustration, and stress (e.g., Bailey and Konstan 2006; Iqbal and Bailey 2005; Mark et al. 2008). Furthermore, task interruptions are

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associated with a decreased satisfaction concerning one's job and performance (e.g., Baethge and Rigotti 2013; Keller et al. 2019).

At the behavioral level, task interruptions can result in forgetting to resume the interrupted task (e.g., Dodhia and Dismukes 2009). If the interrupted task is resumed, more time may be needed to complete the task (e.g., Bailey and Konstan 2006; Marulanda-Carter and Jackson 2012; see Magrabi et al. 2010; Westbrook et al. 2010a, for contradictory findings), and already executed actions are more often repeated or actions to be performed are more often omitted than in uninterrupted tasks (e.g., Altmann et al. 2017; Monk et al. 2004).

In safety-critical domains, such as nuclear power plants (e.g., Griffon-Fouco and Ghertman 1984), car driving (e.g., Gregory et al. 2014), aviation (Loukopoulos et al. 2001, 2009), and healthcare (see, e.g., Grundgeiger and Sanderson 2009; Li et al. 2011, for reviews; see also Grundgeiger et al. 2016), the harmful effects of task interruptions on human performance can contribute to accidents. To come back to the healthcare domain, the repeated execution of an action such as administering a dose of medication to a patient twice or the skipping of to-be-performed actions, such as forgetting to record the administration on the medication chart, so that the dose is possibly administered again by another nurse, can compromise patient safety (Johnson et al. 2017; Westbrook et al. 2010a).

An understanding of the underlying cognitive mechanisms of the disruptive effects of task interruptions on human performance is, therefore, important from both theoretical and practical perspectives. On the one hand, the investigation of performance degradation due to task-interruption demands in controlled laboratory studies conducted in fundamental research can inform theories about the basic operating principles of human cognition in general and about goal-directed behavior (e.g., goal formulation, retention, and execution; Hodgetts and Jones 2006b) in particular. Such theories help to predict the detrimental effects of task interruptions on human performance and well-being. In the applied research domain, these theories and predictions, in turn, can be used as bases for the development of practical recommendations for task environments and software (see, e.g., Iqbal and Bailey 2010, for an exemplary notification management system) which may minimize the deleterious effects of task interruptions. On the other hand, field research can identify human behavior that affects the cognitive processes involved in the resumption of interrupted tasks and highlight understudied topics in laboratory-based research.

As a result, task interruptions have been in the focus of a broad range of research disciplines, including cognitive psychology, computer science, human factors, and healthcare. Each discipline contributes with its own theoretical perspectives and methodological approaches to task-interruption research, leading to an interdisciplinary and method-rich research field with diverse self-reported subjective, physiological, and behavioral measures of task-interruption effects (e.g., Bailey and Konstan 2006; Foroughi et al. 2015a; Lee et al. 2018; McCurdie et al. 2017; Ratwani and Trafton 2008).

To cover the interdisciplinary approach in task-interruption research, both the basic and applied research domains are addressed in the present chapter. A special focus is laid on experimental approaches. At first, a definition of task interruptions and a differentiation from related multitasking constructs are provided. Then the major findings from the basic and applied research domains on the effects of task interruptions on human performance are reviewed. Finally, theoretical accounts that explain these task-interruption effects, along with recommendations for task-interruption management, are presented in the present chapter.

2 Definition of Task Interruptions

Several definitions of task interruptions from various disciplines, emphasizing different characteristic aspects of task interruptions, have been put forward (e.g., Brixey et al. 2007b; Trafton et al. 2003; see also Dodhia and Dismukes 2009). Even though the proposed definitions differ depending on the research question and the cognitive processes of interest, they have numerous aspects in common (Grundgeiger et al. 2016).

In fundamental research, a task interruption is usually defined as a temporary suspension of an ongoing task, referred to as primary task (or main task; e.g., Zijlstra et al. 1999), in order to perform another unexpected task, termed secondary task (or peripheral task, e.g., Lee et al. 2018). The interruption introducing the secondary task is either externally initiated (i.e., external interruption, for instance, by an incoming phone call) or internally initiated (i.e., internal interruption or self-interruption, e.g., by intrusive thoughts; Gonzalez and Mark 2004), and the completion of the secondary task has, at least temporarily, priority over that of the primary task. A crucial defining criterion of a task interruption is, however, that there is the intention to resume the primary task. Consequently, the completion of the primary task is only postponed but this task is not ended.

In contrast to basic research, in applied research, the definition of a task interruption is less consistent. Whereas some researchers propose definitions similar to that usually employed in basic research (e.g., Brixey et al. 2007a), other researchers define task interruptions more generally as situations in which a person is distracted from the primary task, without further specifying whether there is a secondary task that needs to be performed (e.g., Ebright et al. 2003). Moreover, some applied studies do not provide a definition at all (e.g., Christian et al. 2006; see Grundgeiger and Sanderson 2009, for an overview). The inconsistent definitions of task interruptions certainly hamper a comparison of applied studies and their results. However, as elaborated by Grundgeiger et al. (2016), the diversity in definitions is important because in applied research task interruptions are studied from various research disciplines with diverse aims and research questions. As a result, the observed task-interruption situations differ across applied studies.

Initial empirical evidence suggests that both external and internal interruptions occur roughly equally often (e.g., Gonzalez and Mark 2004; Mark et al. 2005). The experimental investigation of internal interruptions is, however, challenging. For example, it is difficult to distinguish internal interruptions from breaks, to identify the reasons for internal interruptions (see, e.g., Jin and Dabbish 2009, for categories of internal interruptions in the context of computer-related activities), and to determine the time in point when the decision is made to interrupt the primary task. As a result, it is difficult to systematically vary the occurrence and timing of internal interruptions. Given these methodological difficulties and the fact that studies on internal interruptions are rather rare (see, e.g., Katidioti et al. 2014, 2016, for exceptions), the present chapter focuses on external task interruptions only.

External task interruptions have a characteristic time course with several serial processing stages. In task-interruption contexts, a primary task is being performed (e.g., preparing a dose of medication) when an alert occurs (e.g., ringing of the phone) signaling a forthcoming interruption by a secondary task (e.g., conversation on the phone). The temporal interval between the onset of the alert for the secondary task and the start of the secondary task (e.g., ringing of the phone and starting the conversation) is the *interruption lag* which is used to disengage from the primary task and to engage in the secondary task. After the completion of the secondary task, the primary task is resumed. The temporal interval between ending the secondary task and restarting the processing of the primary task (e.g., the end of the conversation on the phone and the continuation of administering medications) is the *resumption lag* which is used to disengage from the secondary task and to re-orient to the primary task.

The interruption lag differs in its duration depending on the response requirements of a task-interruption situation. According to McFarlane's (2002) classification of task interruptions, a distinction is made between immediate, negotiated, scheduled, and mediated task interruptions. *Immediate task interruptions* require a prompt stopping of the primary task, regardless of its state of processing, and an instant response to the secondary task (i.e., ringing of the phone indicating an urgent conversation). In the case of *negotiated task interruptions*, one is informed about a pending secondary task, but one is given full control over when to leave the primary task in order to attend to the secondary task (e.g., spelling error underlined in red by a word processing application). Thus, one does not have to handle the secondary task immediately. In the present chapter, a special focus is put on both immediate and negotiated task interruptions. In contrast to these types of task interruptions, *scheduled interruptions* are task interruptions that occur in restricted and prearranged time intervals (e.g., in 40-min cycles), whereas *mediated task interruptions* are indirect interruptions through a mediator. Such mediators use context information to determine when best to interrupt the primary task in order to make the effects of the interruption on performance in the primary task less disruptive (e.g., attention-aware systems).

Task interruptions differ from distractions. They both capture one's attention while one is performing the primary task (Werner et al. 2015). However, distractions merely involve ignoring task-irrelevant stimuli (e.g., to notice a loud conversation during the preparation of a medication administration) but not suspending a task, forming the intention to resume this task, and dealing with an additional task which is required in task-interruption situations (e.g., Clapp and Gazzaley 2012; Grundgeiger et al. 2010).

Task-interruption situations are considered to be a form of multitasking (e.g., Janssen et al. 2015; Salvucci and Taatgen 2011). As in task-interruption contexts, in multitasking situations, multiple tasks, each associated with a separate task goal, are performed in a limited time period. This results in a temporal overlap of the cognitive processes involved in performing these tasks, making the management of multiple task goals necessary (e.g., Hirsch et al. 2018, 2019; for a review, see, e.g., Koch et al. 2018).

In sequential multitasking, multiple tasks are performed in succession and a rapid switching between the tasks is required (see, e.g., Kiesel et al. 2010; Vandierendonck et al. 2010, for reviews). Task interruptions are assignable to sequential multitasking because there is a shift from the primary task to the secondary task, and after having completed the secondary task, a switch back to the uncompleted primary task is required.

However, there are crucial differences between task-interruption and task-switching situations. In task-interruption contexts, when the alert for the pending secondary task appears and one shifts the attention to the secondary task, the primary task is not yet completed and has to be resumed later at the point of its suspension. In contrast to task-interruption situations, the alert and the shift to the secondary task occur in task-switching situations after the completion of the primary task. Hence, there is no need to form the intention to resume the primary task and to maintain this intention, along with the processing state of the primary task, when shifting attention to the secondary task. Rather, a rapid switching between the stimulus-response mappings of completed discrete tasks is called for, possibly involving fundamentally different cognitive processes from those in task-interruption situations (Monk et al. 2008).

In spite of these differences between task-interruption and task-switching demands, both interrupting tasks and switching tasks have been shown to rely on time-consuming and error-prone cognitive processes, as indicated by worse performance in task-interruption and task-switching conditions relative to appropriate control conditions (see, e.g., Kiesel et al. 2010; Koch et al. 2018, for reviews on task switching and Couffe and Michael 2017; Trafton and Monk 2007; Werner et al. 2015, for reviews on task interruptions). The next section provides an overview of how the performance decline in task-interruption situations is assessed and of the major empirical findings of task-interruption research.

3 Empirical Perspective on Task Interruptions

The first studies on task interruptions go back to Zeigarnik's investigation in the 1920s, in which the effects of interrupted and uninterrupted tasks on memory were examined (Zeigarnik 1927; see also Ovsiankina 1928). Since then, many studies using a variety of empirical approaches with diverse behavioral measures of the effects of task interruptions on a number of different primary tasks have been conducted.

The employed primary tasks range from cognitively complex tasks such as problem-solving tasks (e.g., strategic computer game task in Trafton et al. 2003) to elementary stimulus categorization tasks (e.g., a predefined sequence of forced-choice categorization tasks like categorizing digits along their parity and magnitude dimensions in Altmann and Trafton 2015) and tasks relying heavily on motor skill abilities (e.g., copying tasks requiring the typing of presented sentences in Lee et al. 2018). To the most part, the primary tasks in laboratory-based studies are, however, cognitive and complex in nature, rely on memory, and involve a series of subtasks to be performed in order to accomplish the primary task (e.g., Nicholas and Cohen 2016).

Tasks comprising a series of subtasks are referred to as multi-step tasks. Multi-step tasks differ in their procedural characteristics. Whereas *procedural multi-step tasks* require the execution of a predefined series of subtasks without omissions and repetitions (e.g., Altmann et al. 2017), in *non-procedural multi-step tasks*, the goal of the primary task is achievable by various sequences of the subtasks. Thus, the subtask sequence is not predefined but up to the control of a person (e.g., gamble task in Nicholas and Cohen 2016). Irrespective of the procedural characteristics of the primary task, task interruptions generally have an adverse effect on the performance in such multi-step tasks which has been explored based on diverse behavioral measures.

3.1 Measures of Task-Interruption Effects

The characteristic time course of a task interruption with its discrete processing stages has been usually used as the basis for studying task-interruption effects at the behavioral level. From performance in these processing stages, which is typically quantified in terms of processing times and accuracy, inferences are drawn about the underlying cognitive mechanisms of the adverse effects of task interruptions on primary task performance. Frequently analyzed behavioral measures reflecting the time cost associated with task interruptions are the *total time on task*, the *interruption lag*, and the *resumption lag*.

The *total time on task* is the time it takes to perform the primary task when the time spent on the secondary task is excluded (e.g., Lee and Duffy 2015; Lee et al. 2018; Zijlstra et al. 1999). This behavioral measure is typically contrasted across interrupted and uninterrupted primary tasks or across primary tasks performed under different task-interruption conditions. Thus, this measure allows for the assessment of the increase in the processing time of the primary task due to task-interruption requirements. Since the total time on task does not only represent changes in performance immediately after the task interruption but also captures the entire time until primary task completion, it represents a global measure of performance impairments in interrupted tasks that allows for strategic compensation. Compared to the total time on task, the interruption lag and the resumption lag are more fine-grained measures of the performance decline in task-interruption situations.

In operational terms, the *interruption lag* reflects, as outlined above, the time between the onset of the alert for the secondary task and the start of the secondary task processing. During this time period, cognitive processes ensure the preparation for the resumption of the primary task which is required after the interruption and enable an attention switch to the secondary task. The interruption lag can be analyzed in two ways. On the one hand, the length of the interruption lag can be manipulated to explore how the preparation for the resumption of the primary task impacts performance in both the primary task and the secondary task (e.g., Trafton et al. 2003). On the other hand, it can be analyzed how manipulations related to the primary and/or secondary task impact the duration of the interruption lag and, hence, preparatory and switching-related processes (e.g., Altmann and Trafton 2007; Hodgetts and Jones 2006b).

The *resumption lag* is the most frequently analyzed behavioral marker of the harmful effects of task interruptions on performance (e.g., Salvucci 2013). In contrast to the interruption lag, it reflects the time between completing the secondary task and re-engaging in the suspended primary task. During the resumption lag, cognitive processes assure a quick and accurate retrieval of both the primary task's goal and the processing state of the primary task at the point of its suspension. The resumption lag can be analyzed in a number of ways. It can be compared either across primary tasks arising in situations with different task-interruption requirements (e.g., Brumby et al. 2013; Ratwani et al. 2008) or with the inter-action interval which is the time between two consecutive uninterrupted actions in the primary task (e.g., Altmann and Trafton 2004; Blumberg et al. 2015; Ratwani et al. 2006).

Hence, the interruption lag and the resumption lag focus on separate aspects of the underlying cognitive mechanisms of the deleterious effects of task interruptions on performance. The interruption lag is considered as a behavioral marker of preparatory processes facilitating the resumption of the primary task after the secondary task completion and of switching-related processes initiating the secondary task processing. In contrast, the resumption lag is assumed to be a behavioral index of memory retrieval processes and reflects a sort of interruption recovery. Effects of task interruptions beyond this initial resumption of the primary task are covered by the total time on task. Note, however, that all these measures may include some after-effects of previous control states associated with performing the primary task before switching to the secondary task and/or linked to the completion of the secondary task prior to switching back to the primary task (i.e., proactive interference; see Sect. 4.1).

These three behavioral measures quantify interruption effects in terms of a time cost. Task interruptions, however, also increase the vulnerability to errors. Research focusing on the effects of task interruptions on accuracy in the primary task has, in addition to decision accuracy and memory recall (e.g., Edwards and Gronlund 1998; Speier et al. 1999), addressed two types of error, including sequence errors and non-sequence errors which occur in the subtask directly after the interruption (i.e., resumption errors) and/or in the following subtasks (e.g., Altmann et al. 2014; Li et al. 2008).

Sequence errors arise when a subtask in a predefined subtask sequence is repeated or omitted (e.g., repeating an already completed item in a checklist or skipping a to-be-performed item in the checklist; see also Westbrook et al. 2010b). Hence, in the case of sequence errors, the sequence of subtasks within the primary task is resumed from the wrong position (i.e., perseveration and anticipation errors). A specific form of sequence errors is the *postcompletion error*. It refers to the omission of the final subtask of a multi-step task, when the main goal of the multi-step task is accomplished, but an end action is required (e.g., to forget to take the originals after photocopying; e.g., Byrne and Bovair 1997; Li et al. 2008). In contrast to sequence errors that reflect the "loss of place in the procedure," *non-sequence errors* occur when a correct subtask is selected but incorrectly executed (Altmann et al. 2017, p. 222).

Sequence and non-sequence errors can be embedded into a widely used cognitive taxonomy of human errors (Reason 1990; see also Rasmussen 1983). In the framework of this generic taxonomy, besides other types of errors, a distinction is made between memory lapses and slips. Both lapses and slips reflect an incorrect execution of a correct action sequence. Whereas lapses are caused by memory failures, resulting in sequence errors which reflect a loss of place in the action sequence, slips are attributable to attentional failures which can result, in addition to sequence errors, in non-sequence errors reflecting the incorrect execution of a correct step.

In applied settings, the measures vary depending on the different research traditions (McCurdie et al. 2017). McCurdie et al. (2017) summarized the above approaches of seeking causal relations between interruptions and fine-grained indicators of cognitive processes as applied cognitive psychology. The epidemiology approach aims at quantifying incidence rates, distributions, and consequences of interruptions. Few epidemiological studies also sought to investigate the relationship between interruptions and errors (e.g., Westbrook et al. 2010b) but leave aside the cognitive pathways of errors. The quality improvement approach aims at reducing interruption via various interventions and accepts the distractive nature as given. Hence, the measures of quality improvement address error and foremost interruption frequencies. Finally, the cognitive systems engineering approach accepts interruptions as a regular part of work and suggests to measure the effect of interruptions not only on an individual (cognitive) level but to consider the effect of interruptions on a system level such as delayed work process of the interruptee.

Task-interruption research has demonstrated that the disruptive effects of task interruptions are affected by a host of factors. An investigation of such influencing factors is worthwhile because it helps to identify the underlying cognitive mechanisms of task-interruption effects. In the following, the most frequently analyzed factors that influence the effects of task interruptions on primary task performance are presented.

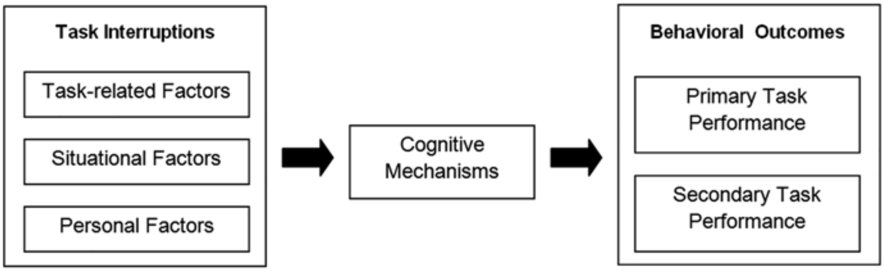

Fig. 1 Factors influencing the effects of task interruptions on performance

3.2 Factors Influencing the Disruptiveness of Task Interruptions

Task-related, situational, and personal factors can influence the disruptiveness of task interruptions (see Fig. 1). *Task-related factors* are represented by the characteristics of the primary and secondary tasks, whereas *situational factors* describe the specific situational circumstances under which the primary and secondary tasks are performed. In contrast to task-related and situational factors, which are independent of the internal characteristics of the person experiencing a task interruption, *personal factors* are intrinsic to the interrupted person.

3.2.1 Task-Related Factors

Task-related factors that impact the performance decline in task-interruption contexts are, for instance, represented by the similarity of the secondary task to the primary task and the complexity of those tasks. A further task-related factor refers to the interruption duration and, hence, to the time it takes to perform the secondary task.

Task Similarity

A number of studies showed that secondary tasks that are similar to the primary task are more disruptive to the primary task performance, as evident in time delays and errors, than dissimilar secondary tasks (e.g., Czerwinski et al. 1991; Gillie and Broadbent 1989; Lee et al. 2018; Oulasvirta and Saariluoma 2004; see also Ledoux and Gordon 2006; Pankok et al. 2017). Some studies have examined the impact of task similarity on task-interruption effects using a secondary task that is identical to the primary task (e.g., Lee and Duffy 2015; Lee et al. 2018) and, therefore, requires the same task operations, whereas other studies have focused on similar primary and secondary tasks which overlap only partially in the required task operations (e.g., Edwards and Gronlund 1998).

There is also a large body of work defining similarity based on modality overlap between the primary and secondary tasks (see, e.g., Lu et al. 2013, for a meta-analysis on the effect of interruption modality). However, studies on the role of modality overlap in task-interruption situations have predominantly focused on task-interruption-handling strategies and used complex task environments in which the primary task is not necessarily postponed due to a task interruption but is partially performed concurrently with the secondary task. The first empirical findings in this domain indicate a cross-modal benefit, meaning that the harmful effects of task interruptions are reduced when the secondary task is presented in a modality different from the primary task (i.e., cross-modal combination, e.g., visual-auditive combination) compared to when it is presented in the same modality (i.e., intramodal combination; e.g., visual-visual combination; e.g., Ho et al. 2001; Latorella 1998; see also Ho et al. 2004).

Moreover, it seems that as opposed to cross-modal interruptions, intramodal interruptions, at least in the case of visual tasks, are postponed for a longer time than auditive and tactile interruptions, given that a person has control over when to engage in the secondary task (e.g., Ho et al. 2004). Other studies, however, indicate that cross-modal interruptions do not necessarily disrupt primary task performance more than intramodal interruptions (e.g., Ratwani and Trafton 2010). Rather, it would be more important whether the processing of the secondary task allows for rehearsal of the primary task. Rehearsal is a mechanism that refreshes transient items in memory through their repeated retrieval or the repeated allocation of attention to them (Baddeley 1986).

Yet, some studies have found no task similarity effect (e.g., Bailey et al. 2000; Eyrolle and Cellier 2000; Speier et al. 1999) which might be accounted for by differences in experimental paradigms, behavioral measures, and the operationalizations of task similarity levels. The similarity between the secondary task and the primary task can be defined, for example, in terms of the resources needed for task processing, the form of information that has to be processed, or the semantic content of the material (e.g., Latorella 1999). Depending on the definition of task similarity, the operationalization of task similarity levels differ across studies, making comparisons of task similarity effects across different task-interruption studies difficult.

Task Complexity

Regarding the role of task complexity in task-interruption situations, there are two lines of research. The first line of research explores how task-interruption effects are affected by the complexity of the primary task, whereas the second line of research examines how task-interruption effects are modulated by the complexity of the secondary task.

The first line of research on the effects of *primary task complexity* indicates that interrupting complex primary tasks increases the time it takes to complete the primary task and, hence, impairs performance. In the case of simple primary tasks, though, interruptions shorten the total time on the primary task, thus improving performance (e.g., Mark et al. 2008; Speier et al. 1999, 2003; Zijlstra et al. 1999). At a more fine-grained level, it has been shown that for simple tasks, the time to perform the first subtask back on the primary task is prolonged (i.e., resumption lag), but the following subtasks are actually performed faster (indicated by interaction intervals) than in uninterrupted tasks, leading to an overall shorter completion time for the primary task (Ratwani et al. 2006). In an experiment on the effect of interruptions on simple and complex medication prescribing tasks, Magrabi et al. (2010) observed no effect of primary task complexity on total time on the task, but complex prescribing tasks had a significantly longer resumption lag than simple prescribing tasks.

Attention narrowing has been proposed to account for the finding that simple and complex primary tasks are differently affected by task interruptions (Speier et al. 1999, 2003). In particular, it has been argued that simple tasks are associated with boredom and monotony. Task interruptions are assumed to make the task more difficult, and, consequently, arousal and stress levels increase and attention narrows, which facilitates the primary task processing after an interruption. In contrast to simple tasks, in the case of complex primary tasks, crucial information might be missed due to arousal and attention narrowing, leading to a decline in primary task performance.

The underlying cognitive mechanisms of the beneficial impact of task interruptions on simple primary tasks are still not fully understood. The first empirical evidence coming from eye movement studies, however, suggests that the speedup is, at least partly, attributable to faster perceptual processing after interruptions (i.e., fixation durations, e.g., Ratwani et al. 2006).

Existing studies generally support the deleterious effect of task interruptions on complex primary tasks (e.g., Monk et al. 2008; see also Szumowska and Kossowska 2017). Therefore, a further line of research focuses on the question of whether the effects of task interruptions on the primary task performance vary as a function of the *secondary task complexity*. A typical finding is that primary task performance is worse when the primary task is interrupted by a complex secondary task compared to a simple one. This performance decline has been observed in terms of increased completion times, resumption times, and error rates in the primary task (e.g., Eyrolle and Cellier 2000; Gillie and Broadbent 1989; Hodgetts and Jones 2006b).

It is worth noting that in some task-interruption studies task complexity was manipulated by varying solely one specific aspect of the secondary task, making the tasks highly comparable across the complexity levels (e.g., arithmetic sums with one-digit numbers vs. two-digit numbers in Hodgetts and Jones 2006b), whereas in other studies two quite different secondary tasks were used (e.g., tracking task vs. *n*-back task in Monk et al. 2008). The reason for such inconsistencies across studies lies in the fact that task complexity is a vague term that is difficult to define adequately.

Task complexity can be specified in various ways, for instance, by the number of required actions, the difficulty of executing these actions, the number of subgoals, and the extent of information to be considered (Byrne and Bovair 1997). Whereas some task-interruption studies defined task complexity in terms of these processing requirements (e.g., Cades et al. 2007; Hodgetts and Jones 2006b), other studies used the term *demands* instead of complexity. In these studies, task complexity was defined with regard to the requirements posed on working memory which determine the extent to which the secondary task interferes with the ability to rehearse the suspended primary task during secondary task processing (e.g., Monk et al. 2008).

Following this line of reasoning, it has been shown, for example, that a shadowing task necessitating little cognitive operations was less disruptive to the primary task performance than an *n*-back task but that the resumption times did not differ depending on whether a 1-back or a more complex 3-back task was presented as a secondary task (Cades et al. 2007). This indicates that task characteristics influencing the ability to rehearse the suspended primary task during task interruptions and, at least partially, varying along with task complexity levels might mediate the role of secondary task complexity in task-interruption effects (Cades et al. 2007; Monk et al. 2008).

To assess the impact of secondary task complexity on task-interruption effects, it is, thus, important for future research to control for task characteristics that vary along with the levels of secondary task complexity. For instance, complex secondary tasks might not only reduce opportunities for rehearsal, but they might also require more time to be processed than simple secondary tasks, making the time it takes to perform the secondary task, and thus the interruption duration, a confounding variable.

Duration of the Secondary Task Processing

A classic finding from memory research is that when simple items (e.g., letters) have to be retained in memory, the recall performance decreases over time and even more so if rehearsal is prevented (e.g., see Lewandowsky and Oberauer 2015, for a review). This effect is observable as a reduced proportion of correctly recalled items, even after very short retention intervals of 3 seconds (Peterson and Peterson 1959; see also Brown 1958; Einstein et al. 2003).

In task-interruption situations, the intention to return to the primary task (i.e., prospective memory; see, e.g., Walter and Meier 2014; West 2011, for reviews from the basic research domain and see, e.g., Loft et al. 2019, for a review from the applied research domain; see also Grundgeiger et al. 2014) and the processing state of the primary task upon the point of its suspension have to be remembered during the execution of the secondary task. Inspired by the findings from memory research, numerous task-interruption studies have investigated how the resumption of the primary task is affected by the time it takes to perform the secondary task and, hence, by the duration of a task interruption.

Different interruption durations—ranging from very short interruptions of a few seconds (e.g., Altmann et al. 2017) to quite long interruptions of several minutes (e.g., Gillie and Broadbent 1989)—were reported in task-interruption research. In most studies, it has been observed that the disruptiveness of task interruptions on the performance in the primary task depends on the duration of the task interruption. Typically, more time is needed when resuming the primary task after a long compared to a short interruption (e.g., Altmann et al. 2014, 2017; Foroughi et al. 2016b; Hodgetts and Jones 2006b; Monk et al. 2008; Monk and Kidd 2008; see also Grundgeiger et al. 2010; Salvucci et al. 2009).

The effect of interruption duration has also been shown in field settings with varying ongoing and interrupting tasks. Intensive care nurses showed longer resumption lags when the interruption duration was longer (Grundgeiger et al. 2010), and emergency physicians were less likely to return to an interrupted task after longer interruptions compared to shorter interruptions (Fong et al. 2017).

For task-interruption durations up to 1 min, a resumption lag profile reflecting a logarithmic function has been identified (see Fig. 2; Monk et al. 2008; see also Foroughi et al. 2016b, for evidence for a power function). This logarithmic function indicates that the resumption times for the primary task increase rapidly for short interruption durations up to around 13 s and begin to asymptote in the time range between 13 s and 23 s. Thus, the slope is steeper for short than long interruption durations. Based on this finding, it was concluded that interruption duration effects are best detectable for very short interruptions, at least for task interruption durations in a time range up to 1 min.

Moreover, it has been shown that resumption times increase more sharply across interruption durations for complex secondary tasks compared to simpler secondary tasks (Monk et al. 2008). Thus, the effects of task interruptions on primary task performance do not only depend on how long the primary task has to be suspended

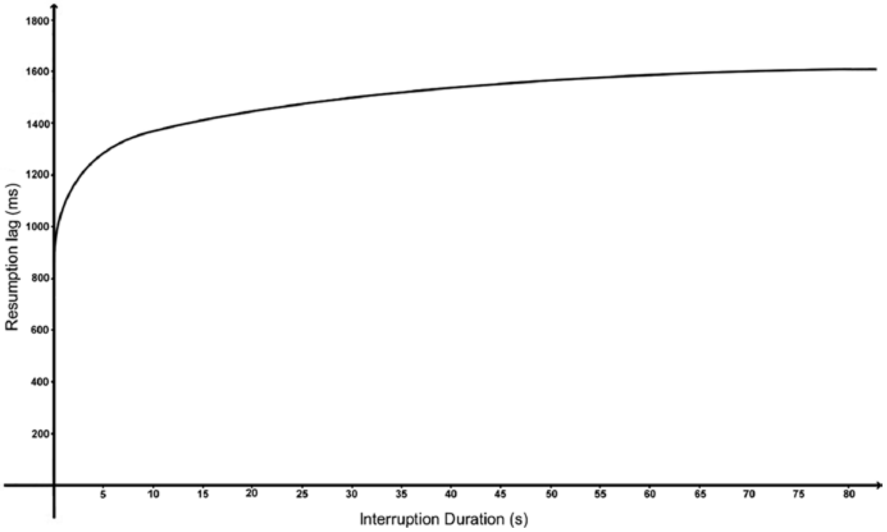

Fig. 2 Resumption lag profile for task interruptions up to 1 min. (Adapted from Monk et al. 2008)

but also on the cognitive demands imposed by the secondary task (see also Borst et al. 2015).

With regard to the effect of task interruptions on the accuracy of the primary task resumption, it has been observed that task interruptions facilitate the occurrence of post-interruption sequence errors (i.e., performing the wrong subtask after an interruption). Furthermore, it has been shown that the interruption duration has an effect on post-interruption sequence errors but no effect on post-interruption non-sequence errors (Altmann et al. 2017), suggesting a disruptiveness of memory processes rather than general attentional resources as the underlying source of task-interruption effects on the performance in the primary task.

The effect of task-interruption duration on sequence errors resembles a standard curvilinear forgetting function. However, when considering the proximity of the incorrect subtask to the subtask that would have been correct in the subtask sequence of a procedural multi-step task, task-interruption duration modulates the occurrence of sequence errors involving a repetition of the subtask performed before the interruption (i.e., pre-interruption subtask) differently from other sequence errors (e.g., repeating the penultimate subtask before the interruption; Altmann et al. 2017). For sequence errors with a pre-interruption subtask repetition, there is a strong increase from very short to short interruption durations (i.e., around 13 s), but this effect levels out with longer task-interruption durations across short, medium, and long interruption durations. In contrast, the increase of the other sequence errors is more gradual and linear across the task-interruption durations, pointing toward a second memory process underlying the performance deteriorations in the primary task induced by task-interruption requirements.

3.2.2 Situational Factors

Situational factors that impact the disruptiveness of task interruptions are, for example, represented by the frequency with which a primary task is interrupted and the point in time when the task interruption occurs. A further influencing factor is whether there are opportunities for preparing to resume the primary task and for using external cues indicating the processing state of the primary task at the point of its suspension.

Task-Interruption Frequency

In the majority of task-interruption studies, the frequency of task interruptions occurring during the primary task processing was held constant (e.g., one interruption per primary task in Hodgetts and Jones 2006b). Since in everyday life we often have to cope with multiple interruptions while performing a task, in some studies, the frequency of task interruptions was systematically manipulated in order to assess the effect of task-interruption frequency on primary task performance. These studies have consistently shown that performance in the primary task declines as the frequency of task interruptions increases, as evident in increased processing times and decreased accuracy (e.g., Basoglu et al. 2009; Lee and Duffy 2015; Zijlstra et al. 1999; see Monk 2004, for a positive effect of frequent interruptions occurring every 10 s). In healthcare, a large observational study (Westbrook et al. 2010a) and an experimental study using a high-fidelity intensive care simulation (Santomauro et al. 2018) reported a dose-response relationship between the number of interruptions and the number of procedural and clinical errors (but see Drews et al. 2019 and Thomas et al. 2017 for null findings in relation to interruptions and nonadherence to protocols).

The investigation of the impact of task-interruption frequency on the primary task performance is, however, linked to the problem that introducing many task interruptions has been shown to result in frustration and a lack of motivation, both leading to a severe decline in primary task performance (e.g., Lee and Duffy 2015). Accordingly, it is difficult to disentangle the direct effects of task-interruption frequency from the indirect effects caused by a lack of motivation or increased frustration.

Task-Interruption Position

Numerous studies aimed to identify moments when best to interrupt the primary task in order to make task interruptions less harmful for performance in the primary task (e.g., Adamczyk and Bailey 2004; Bailey and Iqbal 2008; Cutrell et al. 2001; Czerwinski et al. 2000; Foroughi et al. 2014; Hodgetts and Jones 2006b; Monk et al. 2004). Generally, interrupting a primary task between its subtasks is less disruptive for the performance in both the primary and the secondary tasks than scheduling interruptions during the execution of a subtask (e.g., Bailey and Konstan 2006; Botvinick and Bylsma 2005; Cutrell et al. 2000). More specifically, it has been reported that in the case of interruptions occurring during the execution of the primary task, 3–27% more time to complete the primary task is needed, and that twice the number of errors across tasks are committed, compared to task interruptions occurring between the subtasks of the primary task (Bailey and Konstan 2006).

Based on these findings, it has been concluded that low mental workload moments are more suitable for interrupting the primary task than high workload moments. This is because at such subtask boundaries, the cognitive resources allocated to the subtask are momentarily released, thereby reducing the mental workload before the resources are re-allocated to the upcoming subtask, causing the workload to increase again (Miyata and Norman 1986).

Studies utilizing pupil dilation as a physiological correlate of mental workload showed that mental workload is indeed reduced between subtasks compared to moments during the execution of a subtask and that task interruptions occurring at such low workload moments are less harmful than at high workload moments (e.g., Bailey and Iqbal 2008; Iqbal and Bailey 2005; see also Iqbal and Bailey 2007). These findings are further supported by studies in which the interrupted persons have control over when to engage in the secondary task. In laboratory settings, it has been observed that the secondary task is performed at points of lower workload (Lenox et al. 2012; Salvucci and Bogunovich 2010).

Furthermore, already Zeigarnik (1927) reported that participants showed discretionary behavior by refusing to engage with an experimenter-induced interruption. Field studies showed that the interrupted person frequently takes the liberty to decide when to interrupt the primary task. For example, intensive care nurses finished the task before attending the interruptions in almost 20% of the observed interruptions (Grundgeiger et al. 2010). Similarly, in a field study with software developers, 17 out of 20 participants stated that they finished the current edit before attending the experimenter-induced interruption (Züger and Fritz 2015). These results suggest that individuals actively seek to influence the task-interruption position and these behaviors are likely to aim at reducing cognitive work related to task resumption processes.

Moreover, in an intensive care unit simulation study, Grundgeiger et al. (2013) observed that nurses performing equipment checks were more likely to defer an interruption from a colleague (i.e., ask the colleague to wait for a brief moment) if they could see the next step of their equipment check on the equipment screen. In a series of laboratory experiments, Weng et al. (2017) showed that the visibility of the task step only resulted in a deferral of the interruption if the participant could immediately take the next step in their execution. Overall, only few studies investigated individuals' planned actions and different strategies to handle interruptions in order to understand the decisions for task-interruption points. It is tempting to assume that individuals are likely to aim at minimizing cognitive work related to the task resumption, but the issue is likely to be more complex because even in laboratory-based studies, participants do not always follow this strategy (Katidioti and Taatgen 2014; see also Gray and Fu 2004).

Opportunity to Prepare Task Resumption

Preparatory processes that facilitate the primary task resumption after the secondary task completion have received a great deal of attention in task-interruption research. For example, the interruption lag and cues linked to the primary task and/or to the secondary task can be used to prepare for the recovery from task interruptions.

Based on verbal reports, two types of preparation have been identified to enhance the resumption of the primary task which is required after a task interruption (e.g., Altmann and Trafton 2015; Trafton et al. 2003). These two types of preparation are prospective goal encoding (i.e., "what was I about to do" in the sense of which specific goal or subgoal I was intended to accomplish) and retrospective rehearsal (i.e., "what was I doing" in the sense of which specific goal or subgoal I accomplished prior to the task interruption; Trafton et al. 2003), both aiming to maintain the primary task active during secondary task processing.

The *interruption lag* represents a time window for these preparatory processes because the notification about the pending secondary task has been already presented, and therefore, the imminent suspension of the primary task is expected (see, e.g., Labonté et al. 2016, for the effects of warning on interruption recovery in dynamic settings). Prolonging the interruption lag has been observed to reduce the vulnerability for resumption errors and to shorten resumption times (e.g., Altmann and Trafton 2007; Dodhia and Dismukes 2009; see also Foroughi et al. 2015b; see Altmann and Trafton 2004, for contradictory findings), even if information related to the primary task is not accessible during the interruption lag (e.g., blank screen during the interruption lag).

Making the interrupted persons remember to resume the primary task by presenting an encoding reminder just before the secondary task starts (e.g., the instruction "please remember to return" during the interruption lag) has been shown to have no additional beneficial effect on postcompletion errors beyond that of prolonging the interruption lag (e.g., Dodhia and Dismukes 2009). This indicates that at least for immediate task interruptions, forgetting to resume the primary task might be due to the fact that this intention is not adequately encoded during the interruption lag.

However, interruption recovery can be further facilitated by making the primary task perceptually available during the interruption lag (e.g., screen with the primary task remains visible). This allows environmental cues for the primary task to be accessed and adequately encoded. Such environmental cues provide information about, for example, what action had been performed before the task interruption, which action has to be performed after the task interruption, and/or the spatial location where the primary task was suspended, or where it has to be resumed (e.g., Brudzinski et al. 2007; see also Drew et al. 2018).

The opportunity to encode such environmental cues during the interruption lag has been shown to have beneficial effects on resumption times (e.g., Hodgetts and Jones 2006a; Ratwani et al. 2007; see also Morgan et al. 2013) which can go beyond the effects of solely prolonging the interruption lag (see, e.g., Altmann and Trafton 2004). The completion times for the secondary task, however, have been observed to be not affected by variations of the interruption lag length that specifies the extent to which such cues can be encoded. This indicates that the improvement in the primary task performance is not due to a general speedup after a prolonged time lag but specific to the resumption process (e.g., Trafton et al. 2003). While in some studies the beneficial effects of encoding environmental cues have been even revealed with very short interruption lags of around 2 s (e.g., Hodgetts and Jones 2006a), other studies found these effects only with longer interruption lags of 6–8 s (e.g., Altmann and Trafton 2004; see Altmann and Trafton 2007, for contradictory findings), suggesting that the task environment impacts the time needed to link the cognitive representation of the primary task to environmental cues.

Studies using eye-tracking methods have focused on the perceptual processes involved in resuming the primary task (e.g., Ratwani and Trafton 2008). For this purpose, the patterns of eye movements shown immediately before suspending the primary task were compared with that observed when resuming the primary task. This comparison across pre- and post-interruption fixation locations revealed that the majority of fixations occurring upon primary task resumption correspond to the location of the fixations assessed before the primary task was resumed. However, when the secondary task relied on spatial processing (e.g., mental rotation task), this overlap between pre- and post-interruption fixation locations decreased and resumption times increased, indicating that spatial memory might contribute to the resumption processes (see also Brudzinski et al. 2007; see also Shen and Jiang 2006).

Preparatory processes which support the primary task resumption can occur during the interruption lag, but they can also take place while performing the secondary task. Empirical evidence in terms of verbal reports suggests, however, that the interruption lag is mostly used for preparation (Trafton et al. 2003). At the behavioral level, this finding is confirmed by studies that showed performance in both the secondary and the primary tasks to differ not depending on whether there is the opportunity for preparatory encoding during the interruption lag only or during the entire duration of secondary task processing (e.g., Hodgetts and Jones 2006a). Finally, the notion that environmental retrieval cues are formed at the point of primary task suspension rather than during secondary task processing is supported by eye-tracking studies which observed hardly any explicit fixations to the primary task display during secondary task processing (at least when both tasks are visual; Ratwani et al. 2007).

It has to be noted, however, that the additional time provided by the interruption lag, as opposed to an immediate task interruption, is generally higher than the reduction of the resumption lag (e.g., Morgan et al. 2013). For instance, introducing an interruption lag of 8 s has been reported to reduce the resumption time by 4 s (Trafton et al. 2003), and an interruption lag of 4 s has been found to shorten the resumption time by around 1 s (Altmann and Trafton 2007). This suggests the existence of “structural constraints on recovery that preparatory processing cannot overcome” (Altmann and Trafton 2007, p. 1080).

Whether the opportunity of encoding such environmental cues before engaging in the secondary task contributes to the recovery from task interruptions depends on the availability of these environmental cues after the task interruption. When the task environment changes during secondary task processing, for instance, in dynamically evolving tasks (e.g., in monitoring tasks), the environmental cues are absent after the task interruption, and they might, therefore, not effectively support the retrieval of the primary task at the point of its resumption. Thus, environmental cues are especially efficient when the pre-interruption state of the primary task corresponds to the post-interruption state, as in static tasks (e.g., Hodgetts and Jones 2006a; Morgan et al. 2013; see e.g., Labonté et al. 2019, for positive effects in a dynamic task).

Other studies sought to investigate how the characteristics of the alert for the secondary task, also referred to as interruption cue, affect performance in task-interruption situations. Interruption cues can differ in their characteristics such as modality, the presentation location, the point in time when they are presented, and the amount of information that they provide (i.e., informative interruption cueing; Ho et al. 2004). In this context, it has been shown that advance knowledge about the duration of the secondary task, and thus the interruption duration, affects neither the length of the interruption lag nor the length of the resumption lag (e.g., Hodgetts and Jones 2006b; see also Hameed et al. 2009). Thus, the preparatory processes are not affected by knowing these secondary task characteristics in advance.

External Retrieval Aids

In addition to preparatory processes acting before the task interruption, primary task resumption can also be facilitated by retrieval cues presented only after the secondary task completion and thus upon resumption of the primary task. Such cues, typically, reinforce the last action performed before the task interruption (i.e., previous action cuing) or the first action to be performed after the task interruption (i.e., next action cuing; Jones et al. 2012). Typically, in studies focusing on the effects of such retrieval cues, immediate task interruptions are used and information on the primary task is perceptually not available during secondary task processing. This should prevent persons experiencing a task interruption from encoding their own environmental cues that aid resumption.

Cues related to the status of the primary task have been shown to facilitate the resumption process of the primary task, as evident in reduced processing times and errors, irrespective of whether they highlight the last action before or the first action after the task interruption (e.g., Jones et al. 2012; Kern et al. 2010; McDaniel et al. 2004; Trafton et al. 2005). The cue, however, has to be blatant (e.g., red arrow marking the location of the last action at the screen in Trafton et al. 2005). Subtle cues (e.g., cursor at the relevant location in Trafton et al. 2005; see also Chung and Byrne 2008) have been observed to not facilitate the resumption process better than any cue at all. Since in studies analyzing the total time on task typically no beneficial effects of cueing are reported (Cutrell et al. 2001; Czerwinski et al. 2000), the resumption lag seems to be more sensitive to the beneficial effects of cues than more global measures of primary task performance.

Finally, it has been shown that the deleterious effects of task interruptions on accuracy in the primary task can be reduced when highlighting the end of an interruption. More specifically, postcompletion errors after task interruptions have been observed to occur especially often when the end of the interruption is immediately followed by new task demands. However, marking the end of the interruption (e.g., presenting the cue "interruption end") increases the chance to resume the primary task.

In everyday life and specifically in safety-critical work environments, incidental or explicit cuing of to-be-resumed tasks is likely to play an important and common role. In general, individuals think more often about prospective memory tasks because of external cuing rather than by internal conscious remembering (Kvavilashvili and Fisher 2007). In safety-critical work environments, an aim of the system is to ensure that the system is running safely and the environment has been adapted to foster this aim. For example, 75% of interrupted intensive care tasks had an explicit representation in the electronic patient record (Grundgeiger et al. 2010). If an interrupted task would have been forgotten, the nurse would have been likely to encounter the task at a later point in time in the record. Furthermore, nurses were holding task artifacts such as a medication vial of the interrupted task in their hand while attending an interruption. The use of external reminders to ensure the execution of tasks has been also reported in other domains such as anesthesiology (e.g., Xiao et al. 1997) and aviation (e.g., Hutchins 1995).

3.2.3 Personal Factors

There is a great body of research on the effects of task-related and situational factors on the performance in task-interruption situations, whereas the role of factors intrinsic to the person experiencing the task interruption has been considerably less studied. Even though numerous personal factors are reasonable to affect performance in task-interruption situations, task-interruption studies have mainly focused on the effects of working memory capacity and training. Furthermore, there is first empirical evidence suggesting that personal factors affect interruption handling strategies. In this context, the role of motivational rigidity has been examined.

Working Memory Capacity

In studies addressing the question of how interindividual differences in working memory impact performance in task-interruption situations, working memory capacity is considered as a measure of "interference management" (i.e., maintain information in the face of interference; Foroughi et al. 2016a). The rationale of these studies is that task interruptions act as a form of interference. While performing the secondary task, the information relevant to the primary task has to be maintained in order to facilitate the resumption of this task following the task interruption. At the same time, however, information relevant to the secondary task has to be maintained to ensure the correct processing of the secondary task (e.g., Drews and Musters 2015). Therefore, information pertaining to the secondary task might interfere with that relevant to the primary task.

In research dealing with the role of working memory capacity on the performance decrements in task-interruption situations, participants are typically not only confronted with task interruptions, but they also complete tests for the assessment of their working memory capacity. Either correlations between the scores achieved in such working memory capacity tests and the resumption times and/or the number of errors following an interruption were analyzed or the primary task performance was contrasted across groups of persons with different working memory capacities (e.g., low vs. high in Drews and Musters 2015).

These studies have consistently shown that the negative effects of task interruptions on performance in the primary task and even in the secondary task vary as a function of interindividual differences in working memory capacity (e.g., Drews and Musters 2015; Foroughi et al. 2016a, b; Werner et al. 2011; see also Meys and Sanderson 2013). Generally, persons with low working memory capacity are more susceptible to the harmful effects of task interruptions than persons with high working memory capacity. More specifically, persons with low working memory capacity need more time to resume the primary task and commit more errors upon resumption than persons with a higher working memory capacity. This suggests that a high working memory capacity may make persons resilient to the harmful effects of task interruptions.

In a prospective, direct observation study of emergency physicians, Westbrook et al. (2018) observed that interruptions increased the medication prescribing error rate and that high working memory capacity (operationalized by the OSPAN) protected against errors. Although these results are no direct support that high working memory capacity makes a person resilient to the cognitive effects of interruptions, the results show that working memory can reduce error rates in highly interruptive workplaces like the emergency department.

Furthermore, it has been observed that for both persons with low and high working memory capacity, resumption lags increase when the interruption duration is prolonged. Importantly, working memory capacity mitigates the effects of the interruption duration, meaning that the increase in resumption times as a function of the interruption duration is considerably larger for persons with low working memory capacity than for persons with high working memory capacity (Foroughi et al. 2016b). Based on this finding, it has been concluded that since the effects of interruption duration are observable even in subjects with high working memory capacity, some stages of primary task resumption do not rely on working memory and might reflect other cognitive processes such as visual or perceptual search processes (see also Ratwani and Trafton 2008).

Task-Interruption Training

A well-known finding from cognitive psychology is that performance in a task improves with practice (Newell and Rosenbloom 1981). Such practice effects have also been reported in numerous task-interruption studies in which task interruptions were observed to become less disruptive for the performance in the primary task, as persons become practiced with the tasks and the situation of being interrupted (e.g., Cades et al. 2007; Hess and Detweiler 1994; Zish and Trafton 2014; see Hodgetts and Jones 2006a, for the lack of practice effects). This practice effect was observed in terms of an improved overall performance and a quicker resumption (e.g., Hess and Detweiler 1994; Trafton et al. 2003).

There has been much research to identify the underlying mechanisms of practice effects in task-interruption situations (Cades et al. 2011; see also Hess and Detweiler 1994). For non-procedural multi-step tasks, it has been shown that practicing the primary task alone is not sufficient to reduce the negative effects of task interruptions on primary task performance. Practicing a specific task improves the overall performance in this task, but this practice effect is not generally applicable to situations in which the processing of this task is interrupted. The resumption of the primary task is only facilitated if the task is practiced in a task-interruption context. The performance improvement induced by practice has been, however, observed to be limited to the primary task and secondary task that were trained together. Thus, the effects of practice are specific to the trained pair of tasks and vanish as soon as the primary task is interrupted by another (i.e., untrained) secondary task.

The finding that the effects of task interruptions are not mitigated when either the primary task alone or task interruptions in general are trained indicates that practice effects are not attributable to the improvement of general processes involved in resuming the primary task which act regardless of the specific tasks involved in the task-interruption situation (i.e., general process-specific mechanism). Rather, it seems that practice effects in task-interruption situations are caused by “learning critical components of how to resume for the specific task pair” (i.e., task-specific resumption process; Cades et al. 2011, p. 105).

With regard to the role of interruption training on the performance in procedural multi-step tasks, the picture is more complex. In a procedural multi-step task, practice has been shown to reduce non-sequence errors but to increase sequence errors in the post-interruption trial (Altmann and Hambrick 2017). More specifically, pre-interruption subtasks are more often repeated with practice than without practice. Importantly, the greater susceptibility for sequence errors occurred only for the post-interruption trial but not for the following trials. A similar pattern was observed for resumption times.

It has been argued that, in the case of procedural tasks, practice leads to the situation that the subtasks of the procedural task are performed faster. As a result, the subtasks are represented with less temporal distinctiveness in memory (“just as each telephone pole in the receding distance becomes less and less distinctive from its neighbors”; Crowder 1976, p. 462), which makes them harder to distinguish and retrieve (see Altmann and Hambrick 2017, for a detailed explanation of these findings).

Motivational Rigidity

Besides working memory capacity and training, motivational aspects play a crucial role in task-interruption situations. A special focus has been laid on interindividual differences in motivational rigidity which refers to the need for cognitive closure (i.e., NFC; Kruglanski 1990).

NFC is a basic motivational tendency rather than a motivational deficit and represents a person’s motivation regarding information processing and judgment (Webster and Kruglanski 1994). More specifically, it reflects the interindividual variability in the “desire for predictability, preference for order and structure, discomfort with ambiguity, decisiveness, and close-mindedness” (Webster and Kruglanski 1994, p. 1049), whereby the scores on these scales increase with rising levels of NFC.

Notably, some basic cognitive processes have been observed to vary along with the levels of NFC. Persons with high NFC exhibit a greater focalization on main tasks and an increased ability to ignore task-irrelevant information than persons with low NFC. Thus, high levels of NFC are associated with better selective attention (Kossowska 2007).

Recently it has been reported that NFC affects task-interruption handling strategies, which, in turn, impact performance in the primary task. In a study in which subjects could freely decide whether they wanted to engage in a secondary task or not while performing a primary task (i.e., pop-up window with an “answer” button and an "ignore" button), persons with high NFC scores responded rarely to task interruptions and showed therefore better performance in the primary task than persons with low NFC scores (Szumowska and Kossowska 2017).

4 Theoretical Perspective on Task Interruptions

Different models have been proposed to account for the disruptive effects of task interruptions on primary task performance (see, e.g., Couffe and Michael 2017; Trafton and Monk 2007, for an overview; see also Salvucci and Taatgen 2011). In the following, the most prominent task-interruption models in the domain of cognitive psychology are presented, along with a short description of how they account for the basic findings of task-interruption research. These models focus on task-switching, goal memory, place-keeping, and prospective memory demands posed in task-interruption situations.

4.1 Models on the Task-Switching Component

Task-interruption situations come along with (at least) two task switches. First, persons experiencing a task interruption have to switch from the primary task to the secondary task, and after the completion of the secondary task, a switch back to the primary task is necessitated. Consequently, cognitive processes involved in switching tasks might contribute to the performance in task-interruption situations, and task-interruption effects might be accounted for, at least partly, from the task-switching perspective.

In task-switching research, various models on the detrimental effects of task-switching demands on performance have been put forward. Most of these models are assignable to task-set reconfiguration models (e.g., Meiran 1996; Rogers and Monsell 1995; Rubinstein et al. 2001) and to proactive interference models (e.g., Allport et al. 1994; Allport and Wylie 1999, 2000; Schuch and Koch 2003; see e.g., Koch et al. 2018; Kiesel et al. 2010, for a review).

According to *task-set reconfiguration models*, task execution presupposes the activation of a mental representation of the task, called "task set," in working memory. A task set is an abstract representation that comprises an organization of task-relevant information (e.g., stimuli, responses, stimulus-response mappings, and goals relevant to the task; e.g., Rogers and Monsell 1995) which are needed for task processing from stimulus encoding to responding.[1] It is posited that it is structurally impossible for multiple task sets to be activated simultaneously in working memory.

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[1] Note that in computational models, task sets are defined more formally, meaning that they represent a set of parameters needed to program the model to correctly execute a task (e.g., Logan and Gordon 2001; Schneider and Logan 2014).

When a task switches, the previously relevant task set, thus, has to be reconfigured in accordance with the new task (including, e.g., stimulus-set biasing according to Meiran 2000, and/or retrieval of S-R mappings from long-term memory, according to Mayr and Kliegl 2000) to enable the processing of the new task.

Contrary to task-set reconfiguration models, *proactive interference models* postulate that the performance decline in task-switching situations results from task-set inertia (e.g., Allport et al. 1994). More specifically, it is argued that when a task switches, there is interference between the new task set and the previously used task set because the activation of the old task set persists even after task execution, leading to (positive) priming of this task set. Further interference is assumed to arise from prior inhibition of the currently intended task set, which results in negative priming of this task set (see also Schuch and Koch 2003).

The role of task-set activation in task-switching contexts has been further conceptualized within the scope of the functional decay model (Altmann 2002; see also Altmann and Gray 2008). In contrast to proactive interference models, according to which switching-related performance costs directly result from interference between tasks, this model states that between-task interference calls for cognitive adaptations and that switching-related performance costs reflect such cognitive adaptations.

In particular, the functional decay model posits that the activation of a task set decays as soon as a task set has been selected from memory and that this decay is functional in the sense that it prevents the memory of the current task to interfere with the memory for the next task during its encoding. This notion is compatible with the observation that in mixed-task situations (i.e., task sequences including both task repetitions and task switches), response times for a task presented in a predictable run of task repetitions elevate gradually across successive task repetitions (i.e., within-run slowing when excluding the first task repetition in a series of immediate task repetitions; e.g., Altmann 2002; Altmann and Gray 2002; Poljac et al. 2009). In the framework of the functional decay model, this finding indicates that the task is encoded once and that the task set is used for the duration of the predictable series of task repetitions. Performance is considered to decline in such successive task repetitions due to the activation decay of the task set of the repeated task.

Pre-decay performance in such series of predictable task repetitions occurring in mixed-task conditions is assumed to be achievable by task-cue encoding processes which allow for a rapid rebuild-up of task-set activation. These task-cue encoding processes take time as indexed by the so-called restart costs which reflect slower responses in the first task repetition relative to the subsequent task repetitions occurring in a series of predictable task repetitions (e.g., Allport and Wylie 2000; Poljac et al. 2009). In the case of task switches, it even takes longer for encoding processes to re-activate the relevant task set. This is because there was more time for the decay of this task set during the processing of the previous task than in task repetitions.

Accordingly, both the interruption lag and the resumption lag might reflect, at least partly, cognitive processes related to task-set reconfiguration and/or task-set inertia. Note, however, that models emerging from the task-switching domain are specialized to account for switching between stimulus-response mappings of completed discrete tasks involving a single step rather than for the suspension and resumption of multi-step tasks. Moreover, in task-switching studies, typically, completely overlapping task sets are used (i.e., the same stimuli and responses are employed for the tasks; see e.g., Kiesel et al. 2010; Koch et al. 2018, for reviews), resulting in strong interference between tasks. The primary focus of models on task switching, therefore, lies on the conceptualization of how tasks are selected under situations of strong between-task interference and persisting after-effects of previously performed tasks.

Models from the general task-switching domain might, therefore, contribute to the explanation of the switching component covered by task-interruption situations. They, however, do not specify the cognitive mechanisms underlying the formation of the intention to resume a task and the retrieval of this intention, along with the processing state of the suspended task. These cognitive processes rely strongly on memory and have to be conceptualized in theoretical frameworks covering the specific characteristics of task-interruption contexts. The notion of strong memory reliance is empirically supported by the finding that task interruptions modulate the vulnerability for sequence errors but not for non-sequence errors suggesting memory as the disruptive processes rather than an impairment of attentional processes (Altmann et al. 2017).

Future research should examine whether the factors influencing performance in task-interruption situations affect the switching component or the memory component evoked by task-interruption demands. For instance, it is reasonable that the observed impact of task complexity on the performance in task-interruption situations is not attributable to an effect of task complexity on memory-based processes but to an effect of task complexity on switching-related processes. In other words, it might be more difficult to maintain the intention to resume a primary task and the processing state of this task while performing a complex secondary task compared to a simple one. However, it is also conceivable that it is harder to disengage from a complex secondary task than from a simple one, when switching back to the primary task (see also the strategic task overload management model by Wickens and Gutzwiller 2015).

For this illustrative example, it has been shown that resumption times are higher when task interruptions occur during the processing of a primary task than when they are introduced between primary tasks. Interruptions between primary tasks pose neither demands related to the formation of the intention to resume the primary task nor demands linked to the retrieval of this intention and of the processing state of the primary task (e.g., Hodgetts and Jones 2006b). This suggests that, in addition to a switching-related performance cost, there is probably a memory-dependent performance cost, when tasks are interrupted during their processing.

From this example, it is, thus, evident that switching-related processes alone cannot account for the variety of effects revealed in task-interruption research. Therefore, other models have proposed the involvement of memory-based processes in the suspension and resumption of primary tasks in task-interruption situations.

4.2 Models on the Goal Memory Component

The memory for goals (MFG) model is an influential computational activation-based model of goal-directed cognition which is derived from the ACT-R theory (Anderson and Lebiere 1998). The MFG model was originally developed to account for subgoal suspension and resumption during problem solving (Altmann and Trafton 2002, 2007; see also Trafton and Monk 2007) and can be applied to task-interruption contexts as well. According to this model, behavior is directed by goals which are stored in memory and compete for being selected to control cognition. Goals are defined in the MFG model as a "mental representation of an intention to accomplish a task" (Altmann and Trafton 2002, p. 39). To perform a task, it is, thus, necessary to retrieve the corresponding goal from memory.

The retrieval of goals is postulated to be not different from the retrieval of other elements in declarative memory. More specifically, in the MFG model, the retrieval process is based on the hypothetical construct of activation. It is stated that like other items in memory, goals have associated activation levels and that the goal with the highest instantaneous activation level is the one that is retrieved when central cognition queries memory.

Once retrieved, the activation of a goal decreases gradually over time. The residual activation of old goals forms a source of interference during the retrieval process of a new target goal. The activation level of the most active non-target (i.e., distractor) goal reflects the interference level. The target goal is retrieved from memory when its activation is above the interference level. When the activation level of the target goal is below the interference level, the distractor goal with the highest activation instead of the target goal is retrieved (see Fig. 1 and 2).

In addition to the decay of goals, the MFG model proposes two further components that determine the activation of a goal in memory—first, the goal's history of use, which is specified by the frequency as well as recency of its retrieval (i.e., base-level activation), and second, the goal's relevance to the current context, which is determined by associations of the goal with cues in the instantaneous environmental context (associative activation; Trafton et al. 2003). In other words, frequently and recently retrieved goals are assumed to have a higher activation level than old goals which have been only seldomly retrieved from memory. Moreover, the context to which a goal is associatively linked acts as a cue which primes the goal's activation. Both the mental (i.e., long-term knowledge of the task) and the physical environmental context can act as such a cue.

These two components can help to slow down the decay of a goal, when there is the intention to maintain a goal active. The intention to maintain a goal active in order to resume it at a later time is a fundamental aspect of task-interruption situations. According to the MFG model, the primary task goal decays during its suspension. To resume the primary task, the goal has to be re-activated in the face of retroactive interference originating from the higher activation level of the recently pursued secondary task goal which has decayed less during the interruption. After the interruption, the activation of the primary task goal is assumed to be too low to be able to exceed the interference level. However, rehearsal can reduce the decay of the primary task goal (i.e., retrospective rehearsal or prospective encoding; Trafton et al. 2003), and the activation of the primary task goal can be boosted by environmental cues. To prime the primary task goal, cues have to co-occur with the goal before the goal is suspended and when the goal is resumed.

Hence, in the MFG model, the resumption lag reflects the time needed to re-activate and to retrieve the primary task goal from memory. The interruption lag, given that it is under control of the interrupted person, reflects cognitive processes related to the strengthening of the primary task goal (e.g., rehearsal of the processing state of the primary task and encoding of environmental cues) and to the retrieval of the secondary task goal.

The MFG model makes various predictions about the performance in task-interruption situations and accounts for various findings in task-interruption research. For example, the model allows for deriving predictions about the effects of interruption duration, preparation, task complexity, and external retrieval cues on the duration of the resumption lag.

The notion of an interference level, along with the assumption of goal decay, predicts how the resumption lag is affected by the *interruption duration*. According to the MFG model, the primary task goal is immediately subject to activation decay, when the primary task is interrupted by the secondary task. The time it takes to retrieve a goal is inversely related to the activation of that goal. Since long interruptions provide more time for goal decay than short interruptions, it should take longer to retrieve the primary task goal after a long interruption compared to a short interruption. Consistently with this line of reasoning, numerous studies have observed such an interruption duration effect (e.g., Altmann et al. 2014, 2017; Foroughi et al. 2016b).

Regarding the effect of *preparation*, the MFG model predicts that preparation for the resumption of the primary task shortens the resumption lag. In the model, preparation is conceptualized in two ways. First, rehearsal during the interruption lag and the secondary task processing helps to keep the primary task goal active during the task interruption. Second, creating associative links between the primary task goal and the mental or environmental context boosts the activation of the primary task goal after the secondary task processing. In line with the model's prediction, prolonging the interruption lag and making the primary task perceptually accessible during the interruption lag and/or the secondary task processing have been shown to lead to shorter resumption lags (e.g., Hodgetts and Jones 2006a; Ratwani et al. 2007; Trafton et al. 2003).

According to the MFG model, rehearsal as a preparatory mechanism also accounts for the effects of *task complexity* in task-interruption situations. When rehearsal is prevented, the activation of the primary task goal cannot be kept active during the task interruption, which calls for more time to be re-activated after the task interruption. Complex secondary tasks reduce the rehearsal of the primary task goal because they are associated with a high cognitive demand, decreasing the resources available for such rehearsal processes (see also Werner et al. 2015). Note, however, that some studies provide evidence that rehearsal occurs predominantly during the interruption lag (e.g., Hodgetts and Jones 2006b; Monk et al. 2008). During the interruption lag, cognitive resources do not have to be shared across rehearsal and secondary task processing, which should minimize the effects of task complexity.

The MFG model can finally also account for the beneficial impact of external retrieval cues which are presented after the task interruption and mark the suspended position in the primary task. This is because such cues prime the primary task goal, resulting in an increase of its activation and allowing the primary task to exceed the interference level.

In sum, the MFG model has been used in numerous studies originating from different research domains as theoretical basis for the examination of the effects of task interruptions on primary task performance. From these studies, it can be concluded that the MFG model is a powerful account that can explain a variety of task-interruption effects.

4.3 Models on the Place-Keeping Component

The remember-advance model extends the MFG model with the aim to account for task-interruption effects observed in procedural tasks (Altmann and Trafton 2015; Altmann et al. 2017). Like the MFG model, the remember-advance model incorporates the theoretical concept of activation in the sense that memory always returns the most active item and that memory items are subject to decay. A special focus of the remember-advance model lies on errors at the point of primary task resumption, particularly sequence errors including a repetition of the pre-interruption subtask.

A procedural task involves a predefined sequence of subtasks that has to be performed in a predescribed order without repeating or skipping subtasks. Thus, to perform a procedural task correctly, a person has to keep track of the current position in a predefined subtask sequence, and when a subtask is finished, the person has to select the correct consecutive subtask. This cognitive process is known as "place-keeping." The remember-advance model holds that place-keeping relies on two interacting memory systems—the episodic memory and the semantic memory.

The episodic memory stores representations of recently performed subtasks. Hence, there is a representation for each completed subtask. These representations are assumed to decay as time passes, in order to protect the system against proactive interference arising from permanently encoding new subtasks. As a result, the representation of the most recent subtask is the most active, followed by that of the next recent subtask, and so on. The current position in the activation level ranking of recently performed subtasks is marked by the most active representation.

The semantic memory is assumed to store a representation of the whole subtask sequence. In this representation, each subtask is associatively linked with the immediately following subtask, called "successor," and activation spreads from the currently relevant subtask to all successors. Spreading activation is, however, postulated to attenuate with each additional link, creating an activation level ranking of the subtasks to be performed. In this ranking, the next subtask is the most active (i.e., successor 1), the subtask after that (i.e., successor 2) is less active, and so on. Thus, there is an implicit memory for the next subtask to be performed.

The key theoretical premise of this model is that the selection of the next subtask is determined on the basis of two stages—the remember stage and the advance stage. In the context of the remember stage, the representation of the just-performed subtask is retrieved from episodic memory due to its high activation level compared to the representations of other subtasks. At the advance stage, the representation retrieved from episodic memory is employed to identify the successor of the most recent subtask. Spreading activation originating from the representation of the just performed subtask is strongest for the immediate successor of the previously performed subtask. As a result of this priming mechanism, the immediate successor is most active and is retrieved.

According to the model, sequence errors occur because the episodic representation of more recently performed subtasks decays faster than those for older subtasks. The subtask just performed is referred to as predecessor 1, the subtask performed before this subtask as predecessor 2, and so on. Consequently, the episodic representation of predecessor 1 decays faster than that for predecessor 2. After a task interruption, the relative distance between the activation levels of these episodic representations is reduced, increasing the probability for erroneously selecting predecessor 2 instead of predecessor 1. When the advance stage specifies the successor based on this inappropriate input, a sequence error consisting of a repetition of the subtask just performed before the interruption occurs. Errors from this type are predicted to occur more likely than errors reflecting the repetition of older subtasks because it is assumed that episodic representations of previously performed subtasks are too strongly decayed to be selected.

Most importantly, to account for task-interruption effects, the model incorporates a rehearsal mechanism that maintains the representation of the pre-interruption subtask active in episodic memory during task interruptions. In the framework of this model, rehearsal is defined as any form of repeating or saying something out loud that helps to identify the suspended position within the subtask sequence of the primary task upon resumption. The subtask executed immediately before the task interruption (i.e., retrospective rehearsal), the subtask to be performed after the task interruption (i.e., prospective goal encoding), or both subtasks can be the target of those rehearsal processes. Moreover, the subtask itself or some other cognitive codes which are derived from the subtask sequence (e.g., assigning to each subtask a number indicating its position within the subtask sequence and rehearsing the position number instead of the subtask itself) can serve as the target of rehearsal.

Generally, it takes time to set up rehearsal. During this time, the pre-interruption subtask decays relative to the pre-pre-interruption subtask, making the pre-pre-interruption subtask more likely to be retrieved. Once rehearsal processes are set up, rehearsal, however, protects the pre-interruption subtask against decay, whereas the other subtasks decay, increasing the probability that the pre-interruption subtask is retrieved compared to the other subtasks. Therefore, the model predicts that sequence errors strongly increase with short interruptions which do not provide enough time to set up rehearsal and that this effect levels out as soon as rehearsal starts.

The remember-advance model accounts for the same task-interruption effects like the MFG model. The remember-advance model is, however, specialized for procedural multi-step tasks and allows, therefore, also for explaining sequence errors which have been examined in numerous task-interruption studies. Since, however, in task-interruption situations, prospective intentions are formed, many studies also analyzed task-interruption effects from the perspective of prospective memory.

4.4 Models on the Prospective Memory Component

Prospective memory is defined "either as remembering to do something at a particular moment in the future or as the timely execution of a previously formed intention" (McDaniel and Einstein 2007, p. 25). Accordingly, prospective memory represents a memory for future intentions. Important definitional characteristics of this type of memory are that at an appropriate moment persons have to remember on their own (i.e., self-initiated remembering) to accomplish a previously formed intention without explicit prompt and that persons typically deal with another ongoing task when prospective remembering is required (McDaniel and Einstein 2000).

Prospective memory relies on two components—a prospective and a retrospective component. The prospective component refers to the ability to remember at an appropriate moment that there is an intention to be executed. The appropriate moment is determined by a specific point in time (e.g., remembering to administer a dose of medication at 8 am, i.e., time-based prospective memory) or a specific event (e.g., preparing a medication dose before entering the patient's room, e.g., Einstein and McDaniel 1990). In contrast, the retrospective component reflects the ability to specify what is to be done (e.g., remembering the dose to be administered; see, e.g., Cohen et al. 2003, for more details).

Different theoretical views on prospective memory have been proposed. These views differ with regard to the cognitive processes that are postulated to underlie prospective memory performance. Generally, a distinction is made between the monitoring view, the automatic association view, and the multi-process view (e.g., Dismukes and Nowinski 2007; McDaniel and Einstein 2000).

According to the *monitoring view*, prospective memory relies on attentional and working memory processes which in turn are assumed to depend on limited cognitive resources (e.g., Smith 2003). More specifically, it is stated that after the formation of a prospective intention, the intention is maintained active in the working memory, and the environment is constantly monitored for cues which indicate an opportunity to execute the intention.

In contrast to the monitoring view, in the context of the *automatic association view*, it is assumed that prospective memory relies on long-term memory (e.g., Einstein et al. 2005). Specifically, the formation of a prospective intention results in an associative link between the intention and cues. Such cues can be located in the internal environment (e.g., internal stimulus like hunger) or the external environment (e.g., external stimulus like an alert) of a person (Dismukes and Nowinski 2007). When a person is confronted with such a cue, the intention is automatically retrieved from long-term memory, provided that the cue is strongly linked to the intention, for example, due to prior rehearsal (see Dismukes and Nowinski 2007, for an account of the retrieval process of prospective intentions which partly resemble the theoretical assumptions postulated in the framework of MFG model).

Finally, the *multi-process view* integrates the monitoring and the automatic association view into a single theoretical framework (McDaniel and Einstein 2000; Scullin et al. 2013). According to this framework, both working memory and long-term memory underlie prospective memory performance. Which memory system is used in a specific situations is determined by the characteristics of the situation and the nature of the prospective memory task.

Importantly, task interruptions can be considered as representing a prospective memory task (e.g., Dodhia and Dismukes 2009; Edwards and Gronlund 1998). This is because in task-interruption situations, when the primary task is deferred, the intention is formed to resume the primary task after the task interruption which is reflected by the duration of the interruption lag. Subsequently, the interrupted person has to recall this previously formed intention after the completion of the secondary task which imposes demands on prospective memory and which is indexed by the resumption time. Forgetting to resume the primary task can, thus, be interpreted as a prospective memory failure (Grundgeiger and Sanderson 2009).

From the theoretical views on prospective memory outlined above, different predictions about the effects of task interruptions on performance in the primary task can be derived. These predictions relate to the effects of the complexity of the secondary task, the opportunity to prepare for resuming the primary task, and the existence of external retrieval cues.

Regarding the effects of *task complexity*, the monitoring view predicts that resuming the primary task is more difficult in the case of a complex than in a less complex secondary task. This is because limited cognitive resources have to be shared across monitoring opportune moments for completing the primary task and the processing of the secondary task for which the needed resources should increase with the complexity level. The sharing of the limited resources is also expected to impair performance in the secondary task. In contrast, the automatic association view predicts no effect of task complexity on the resumption of the primary task due to shared limited cognitive resources because intention retrieval is expected to occur automatically. However, it has been argued that the complexity of the secondary task might affect the extent to which cues are processed or attend to (Dismukes and Nowinski 2007) which, in turn, can modulate resumption performance.

From the prospective memory perspective, in addition to task complexity, *preparation* plays a crucial role in the resumption of the primary task. When the primary task is suspended, the intention to resume this task has to be formed and cues in the mental and/or physical environment triggering retrieval of this prospective intention have to be encoded. When interruptions occur abruptly and attract attention quickly, these formation and encoding processes might suffer due to a lack of time and due to distraction (Dodhia and Dismukes 2009). In line with existing findings from task-interruption research (e.g., Hodgetts and Jones 2006a; Ratwani et al. 2007; Trafton et al. 2003), prolonging the interruption lag, along with providing perceptual information related to the primary task which allows for the encoding of environmental cues, is expected to improve resumption performance.

Note that task interruptions in prospective memory studies are typically examined in other experimental settings than in typical task-interruption studies. In typical task-interruption studies, the suspended primary task is presented again after the interruption (e.g., primary task display in a visual task), and the resumption time and accuracy (i.e., resume the primary task on the suspended processing state instead of repeating or skipping subtasks) are measured when persons re-engage in the primary task. In prospective memory studies, however, the primary task is not presented again after the completion of the secondary task; instead, persons are presented with a new ongoing task. These studies focus on whether persons remember to resume the primary task before starting to perform the new task. Thus, prospective memory studies provide a complement to typical task interruption studies in the sense that they allow for investigating resumption failures, thereby providing additional insights into the underlying mechanisms of task suspension and resumption.

5 Recommendations for Task-Interruption Management

It is generally accepted that task interruptions, even those lasting no more than a few seconds, have a disruptive effect on cognitive performance (see, e.g., Couffe and Michael 2017; Trafton and Monk 2007, for reviews). How these negative effects can be mitigated is a crucial question. From laboratory-based studies on task interruptions, numerous recommendations can be drawn for task-interruption management that facilitates performance in task-interruption situations.

Recommendations

- Interrupting complex primary tasks should be avoided, especially if the secondary task is similar to the primary task.
- Long task interruptions should be avoided.
- Opportunities to prepare for the resumption of the primary task should be provided, and, if possible, the primary task should remain perceptually available during the interruption lag.
- External retrieval aids for the primary task should be provided (e.g., highlighting the end of the task interruption and presenting blatant retrieval cues for the processing state of the primary task after the completion of the secondary task).
- The primary task or a subtask of the primary task should be completed before shifting attention to the secondary task.

- Tasks in highly interruptive environments of critical safety domains should be assigned to persons with high working memory capacity rather than to those with low working memory capacity.

In summary, it can be concluded that the existing task-interruption studies conducted in fundamental research allow for the derivation of first recommendations concerning effective task-interruption management. Note, however, that those highly controlled laboratory studies were conducted to develop theories on human cognition rather than to test the effects of task interruptions in applied settings. Whether and, if so, how the recommendations derived from basic research on task interruptions are effectively feasible in everyday life in general and in daily working life in specific needs to be examined.

Future research should therefore integrate at the theoretical level the research line on task interruptions with that on task switching or the different research lines on multitasking in general. This would help to achieve theoretical breakthroughs in the understanding of the cognitive mechanisms that underlie performance in single-task and multitasking contexts. Based on this understanding, it would be easier to translate basic research findings into applied settings, and, at the same time, problems in applied setting would facilitate theoretical developments in fundamental research. Hence, further recommendations for task-interruption management necessitate a theoretical integration of fundamental and applied research.

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Language Multitasking

Andrea M. Philipp and Mathieu Declerck

1 Bilinguals, Multilinguals, and Multilingual Language Processing

How many different languages have you encountered today? When listening to a radio show, you might have heard songs in different languages (some you might not even know). When talking to your colleagues, you might have used different languages. Maybe you even attended a language-learning class or helped your children with learning a foreign language at school. There might have been a number of different situations in which you have perceived or produced different languages. In this chapter, we focus on such multilingual situations.

To get a better understanding of the term language multitasking, we first resort to a definition of the term multitasking provided by Koch et al. (2018). The most important aspect of their definition of multitasking is that multitasking occurs "when cognitive processes involved in performing two (or more) tasks overlap in time" (Koch et al. 2018, p. 558), that is, it is not important that the tasks itself overlap in time but that the situation requires to maintain two tasks in working memory at the same time. As there is a large amount of empirical evidence that the two languages of a bilingual person become activated or are active simultaneously (e.g., Costa et al. 2000, for a language-production task; Schulpen et al. 2003, for a language-perception task), we can assume that language multitasking happened in all of the examples given above – even when the two languages were not used (i.e., perceived or produced) at the very same time.

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Of course, on the basis of this definition, language multitasking might also refer to situations in which the same language is used for more than one task. Basically, in most studies on multitasking, participants would not be able to perform the tasks without using language. For example, in a study by Hazeltine et al. (2002), participants had to perform one visual task and one auditory task. In the auditory task, a tone had to be categorized depending on its height and a verbal response (i.e., "one," "two," or "three") had to be given. Obviously, language was necessary to perform this task. Yet, even in the visual task, in which a spatially compatible key had to be pressed in response to a visually presented stimulus, verbal coding of the spatial position was possible. Thus, it is hard to imagine multitasking that does not require any form of language. Similarly, when considering situations in real life, multitasking might occur in situations that comprise different tasks in one and the same language. For instance, while writing a report, one might additionally talk to a colleague or want to listen to one's child talking about their day while simultaneously reading a recipe.

Taken together, language multitasking could be seen as a very broad field. Nevertheless, we will restrict this chapter to those situations in which not only two tasks using language (in a very broad definition) are explored but specifically to situations in which indeed two different languages (i.e., usually the native language of a person [first language, L1] and a foreign language [second language, L2; third language, L3; and so on]) play a role. Put differently, we mainly discuss situations in which people switch between two different languages.

Importantly, however, we believe that findings and theoretical knowledge that are derived from these language-switching situations can be transferred to other language multitasking situations. Previous studies have already demonstrated that switching between languages can also be compared to switching between a dialect and its standard language (Declerck et al. 2021c; Kirk et al. 2018; Kirk et al. 2021; Scaltritti et al. 2017; Vorweg et al. 2019). Further, basic empirical findings observed in language switching were also present when switching between formal and informal language used in the same language (Declerck et al., 2020a). Thus, at the end of this chapter, we are going to discuss whether or not language switching (and language multitasking) is something special and different from other types of task switching (or sequential multitasking) or whether there are more commonalities than differences. Yet, before we come to that point, we first introduce those participants that usually contribute to language multitasking studies, that is, we refer to potential definitions of bilinguals and describe (multilingual) language processing and language control. We will also introduce the language-switching paradigm and review language switching in both language perception (or comprehension) and language production.

1.1 Bilinguals and Multilinguals

Many people know more than one language. A survey of the European commission in 2012 (https://europa.eu/eurobarometer/surveys/detail/1049) collected data from more than 26,000 people across 27 different countries. The survey revealed that

54% of the participants indicated themselves as being able to have conversations in at least one foreign language. The percentage differed, however, largely between countries. Whereas many Dutch participants indicated to be able to communicate in at least one (94%), two (77%), or even three (37%) foreign languages, a relatively high percentage (61%) of participants in the United Kingdom indicated that they could not use any other languages than their native language for a conversation. Of course, this difference is largely biased by the fact that English is one of the most common foreign languages spoken in Europe and beyond. Yet, this example already points to the fact that the ability to communicate in more than one language considerably varies both between individuals and between local regions (within or between countries).

In the survey reported above, participants were asked whether they can communicate in one or more languages. The ability to communicate in a foreign language may be one criterion to define a person as bilingual. People with knowledge in at least one foreign language can range from knowing a few words to being native-like in two languages. Thus, you sometimes find the categorization of people who learned two languages from an early age on and are equally proficient in two languages (often referred to as balanced bilinguals), on the one hand, and people who learned a second language later in life and show a clear proficiency difference between languages (usually referred to as L2 learners), on the other hand (for an extensive discussion of different forms of bilingualism, see Beardsmore 1986). Yet, it is important to note that there is neither a general agreement on when a person is called monolingual, bilingual, or even multilingual (Luk and Bialystok 2013) nor is there a clear, standardized distinction between L2 learners and balanced bilinguals. Rather, recent reviews on bilingualism (e.g., De Bruin 2019; Surrain and Luk 2019) highlighted a number of language aspects that can differ between bilinguals, like the age of language acquisition, frequency of language use, the language proficiency in each of the languages, the fluency of language use, and many more (also note that both language proficiency and language fluency can also differ between reading, listening, speaking, and writing). Further, these factors can also differ across the life span (Anderson et al. 2020).

Against the background of the inconsistent definition of bilingualism and multilingualism, we decided to mainly refer to bilinguals rather than multilinguals in this chapter. Further, we adopt a very general view on bilinguals (i.e., being able to at least communicate in two languages). Yet, as most research is done on L2 learners, the bulk of research reported here will apply primarily to bilinguals who know a second language (irrespective of the age of acquisition) but have a dominance difference between their two languages (for an attempt to measure such a dominance difference, see, e.g., Marian and Hayakawa 2021; see also Gullifer and Titone 2020; Treffers-Daller 2019).

At this point, it is also interesting to note that the focus on language proficiency and potential dominance differences between languages constitutes a theoretical and methodological difference between task switching (and multitasking in a more general sense) and language switching. In language-switching studies, the language proficiency of participants is typically assessed before or after the experiment itself through self-ratings, language questionnaires (e.g., LEAP-Q, Marian et al. 2007;

see also Kaushanskaya et al. 2020), or language proficiency tests (e.g., LexTALE, Lemhöfer and Broersma 2012; MINT, Gollan et al. 2012; for an overview see Peña et al. 2021). In contrast, in task-switching studies, the performance of participants is typically not tested explicitly by an unrelated "task-proficiency test." If at all, the performance in each of the tasks is derived from pure task blocks in which only one task is performed. Yet, one of the most seminal studies focusing on dominance differences between two languages (i.e., Meuter and Allport 1999) was based on a task-switching study (Allport et al. 1994, Experiment 5) in which participants switched between two tasks with a different dominance (word reading and color naming of Stroop stimuli). Whereas the matter of dominance (or a performance difference that already exists prior to the experiment) became a major topic in language switching, it only received relatively little research attention in task switching (but see, e.g., Monsell et al. 2000) and multitasking. Rather, the influence of training/practice in the course of an experiment gained importance in both task switching (e.g., Strobach et al. 2012) and dual-tasks studies (e.g., Schumacher et al. 2001; for a review see Strobach 2020). The influence of training is also a matter of debate in language switching (e.g., Wu et al. 2018). Yet, in most language-switching studies that refer to training, training is seen on a larger scale as a life-long practice. Thus, this research bridges the areas of task switching and language switching as important research questions whether life-long practice in language switching has positive effects on other domains like task switching and multitasking (see, e.g., Bialystok et al. 2004; Prior and MacWhinney 2010). We will return to this discussion when we focus on commonalities between language switching and task switching.

1.2 (Multilingual) Language Processing and Language Control

Most people perceive and comprehend (different) language(s) every day in an either auditory (in case of spoken language) or visual (in case of written or signed language) way. A specific feature of language perception is that we can even perceive multiple languages at the same time, for example, when traveling in a crowded train and people sitting around us talking in different languages. Alternatively, we may, for example, see a sign telling us "welcome" in different languages (see Fig. 1).

These examples already indicate that language perception is at least partially driven bottom-up by hearing or seeing language (for models of auditory language perception, see, e.g., Marslen-Wilson 1987; McClelland and Elman 1986; for a model of visual language perception, see, e.g., McClelland and Rumelhart 1981). In language perception, such auditory or visual information is analyzed and compared to representations stored in the mental lexicon, so that semantic meaning can be retrieved.

Welcome
Willkommen
Bienvenue
Tervetuloa
Croeso
歡迎
добро пожаловать
Καλώς ήρθες
ברוך הבא

Note: The languages included are (from top to bottom) English, German, French, Finnish, Welsh, Chinese (traditional), Russian, Greek, and Hebrew. Translations from the English word welcome were obtained by Google translator (https://translate.google.de/).

Fig. 1 Welcome in different languages

Note: The languages included are (from top to bottom) English, German, French, Finnish, Welsh, Chinese (traditional), Russian, Greek, and Hebrew. Translations from the English word welcome were obtained by Google translator (https://translate.google.de/)

An important assumption in bilingual or multilingual language perception is a language non-selectivity (see, e.g., Grosjean 1988; Shook and Marian 2013), that is, each auditory or visual input will activate corresponding representations in the mental lexicon – irrespective of which language these representations belong to (see, e.g., the different variants of the Bilingual Interactive Activation [BIA] model [Dijkstra and Van Heuven 1998, 2002; Grainger et al. 2010]). Activated word representations, on the one hand, will inhibit other word representations and, on the other hand, activate their corresponding language node (mental representation of the language), which in turn also inhibits competing language nodes and the word representations of that competing language. This way, the semantic meaning of the representation with the highest activation can be retrieved, leading to the comprehension of the perceived word.

When we now turn to language production, the process (even in monolingual language production) starts with the activation of a nonverbal concept. In spoken language, this concept is then transferred into a linguistic format (for models of speech production, see, e.g., Caramazza 1997; Levelt 1992). This includes the selection of the correct lemma (i.e., the abstract word form) and its phonological encoding. In the end, the word can be articulated. For written language production, it was sometimes argued that the same processes (including the phonological encoding) take place (e.g., Miceli et al. 1999). Yet, there is also evidence that a lemma can directly be transferred to an orthographic form before being written (Rapp et al. 1997).

In contrast to the possibility of hearing or seeing different languages at the same time, language production (i.e., speaking or writing) is typically restricted to one language at a time as we cannot utter several words at the same time. An interesting exception here are bimodal bilinguals who can perform code blends, that is, the simultaneous production of a spoken word in one language (e.g., English) and a sign in another language (e.g., American sign language; for reviews on bimodal bilinguals see Emmorey et al. 2008, 2016).

Despite this difference in language perception and language production, one similarity is the assumption of language non-specificity. More specifically, a critical aspect of bilingual language control is the selection of the correct lemma in the correct language. Most models nowadays assume that lexical activation is language non-specific (see, e.g., the inhibitory control model [ICM], Green 1998), that is, a nonverbal concept will activate the corresponding translation-equivalent lemmas in all languages known by the person (e.g., De Groot et al. 2000; Schulpen et al. 2003). For example, thinking about a barking animal will activate the English lemma *dog*, the German lemma *Hund*, and the Spanish lemma *perro* in a trilingual English/German/Spanish speaking person. When this person now intends to produce the word in English (irrespective of the specific format: spoken or written), language control is necessary to allow a fast and accurate production of the correct lemma. According to the ICM (Green 1998), a key mechanism in language control is inhibition of the non-target language(s), that is, depending on the language schema (e.g., the intention to name the barking animal in English), the currently irrelevant languages will be inhibited to allow the selection of the correct lemma in the relevant language.

Whereas the focus of the ICM is on language production and previous versions of the BIA have focused on language perception, the BIA(d) (Grainger et al. 2010) has incorporated both production and perception processes. In this model, production-based language control is *endogenous*, which entails that the goal to speak a specific language will activate the corresponding language node, which will inhibit other language representations. Perception-based language control, on the other hand, is *exogenous*, being driven by the language of the stimulus, which automatically activates its corresponding language node, in turn resulting in inhibition of other language representations. Taken together, both production and perception rely on similar inhibitory processes regulated by language nodes in this model.

There are different ways to explore bilingual language control and the proposed inhibitory control processes. For example, one may look at lapses of language control by exploring involuntary language intrusions (e.g., Declerck et al. 2017b; Gollan et al. 2014b). Further, one may examine conflict monitoring when more than one language is presented, as, for example, in a bilingual flanker task (e.g., Eben and Declerck 2019). Yet, most research was conducted by means of the language-switching paradigm. The language-switching paradigm hereby represents a situation in which language multitasking takes place as participants switch between two (or even three) languages from one trial to the next.

Empirical evidence further suggests that language control mechanism (as measured in the language-switching paradigm) can change both with an increasing proficiency in two languages (for a discussion, see Costa and Santesteban 2004) and with the type of language context (see the adaptive control hypothesis by Green and Abutalebi 2013). More specifically, Green and Abutalebi (2013) distinguished between a single-language context, in which only one language is relevant; a dual-language context, in which a person switches between two languages; and a dense code-switching context, in which a person voluntarily intermixes two languages. The main difference between the dual-language context and the dense code-switching context is that in a dual-language context, two languages are relevant but need to be selected depending on the specific situation, whereas the two languages can be intermixed in a dense code-switching context. For example, when two Spanish-Catalan bilinguals in Barcelona communicate with each other, they can intermix both languages without any issues even within the same sentence or phrase. This resembles a dense code-switching context. If one of these Spanish-Catalan bilinguals later meets with a Spanish and a Catalan monolingual, he/she needs to select the correct language according to the interaction partner, which resembles a dual-language context. Such a dual-language context, thus, requires a relatively high level of inhibitory language control to act according to a given situation.

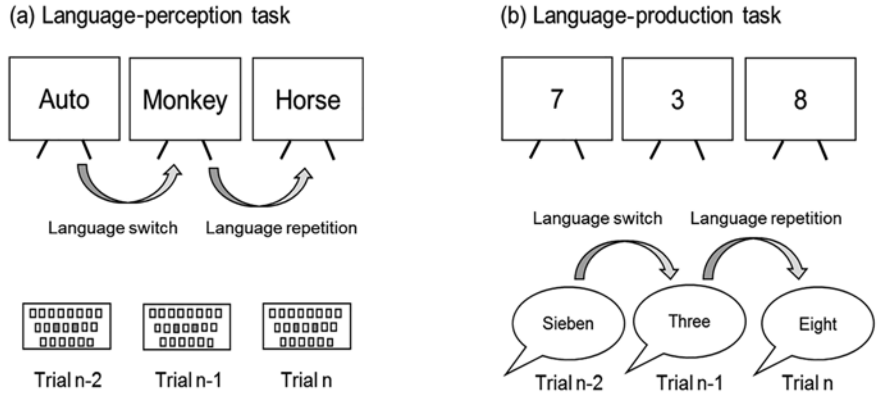
In the following section, we discuss these language contexts and their relation to different variants of the language-switching paradigm. By doing so, we also provide an overview of research using the language-switching paradigm and the most typical findings in both language perception and language production.

2 The Language-Switching Paradigm

2.1 Language Switching in Production and Perception Tasks

In the language-switching paradigm, participants are asked to perform a language task in one of (typically) two languages in each trial – and to switch between these languages on a trial-to-trial basis (for reviews see Blanco-Elorrieta and Pylkkänen 2018; Declerck and Philipp 2015a), that is, when using a language perception task, participants may be asked to categorize a visually presented word in terms of the size (e.g., smaller or larger than a shoebox) or animacy (i.e., living or nonliving) of the corresponding object (see Fig. 2 panel a). In this case, language switching refers to the stimulus that is presented in one or the other language, whereas the response is typically language-unspecific (e.g., a two-choice manual keypress). Further, the language of the stimulus already defines the target language in every trial as the stimulus is language-specific (i.e., it belongs to only one of the potentially relevant languages). One notable example that relied on the language-switching paradigm with a language perception task is Macizo et al. (2012, Experiment 2 and 3). In this study, Spanish-English bilinguals were asked to categorize written words as being either living or nonliving. In turn, the stimuli were language-specific and could either be presented in Spanish or English throughout each block, whereas responses were given by pressing one of two response keys (e.g., Thomas and Allport 2000; Jackson et al. 2004).

In contrast, when using a language-production task, participants are typically asked to name a visually presented digit or picture in one or the other language (see Fig. 2 panel b). In this case, the stimulus is language-unspecific and language



Note: In the language-perception task, participants have to press one key when the object that is named on the screen is living and another key when the object is non-living. In the language-production task, the participants have to name the digit presented on the screen.

Fig. 2 Language switching in (**a**) a language-perception and (**b**) a language-production task
Note: In the language-perception task, participants have to press one key when the object that is named on the screen is living and another key when the object is nonliving. In the language-production task, the participants have to name the digit presented on the screen

switching refers to the response (spoken or writing-naming response). Thus, participants need additional information regarding which language must be used in a given trial (e.g., through a colored frame around each stimulus that has previously been linked to one of the two languages; please note that this is not depicted in Fig. 2 panel b). The stimulus itself is language-unspecific as it activates the corresponding lemmas in both potentially relevant languages (cf. Green 1998). A prominent example is the study of Meuter and Allport (1999), in which bilinguals who knew English as their L1 or L2, next to another European language, were asked to name visually presented digits (1–9) in either their L1 or L2 (e.g., Costa and Santesteban 2004; Philipp et al. 2007).

Next to these prototypical tasks, which are clearly related to language perception or language production, combinations of language perception and production are also possible (e.g., Gambi and Hartsuiker 2016; Liu et al. 2021; Peeters et al. 2014). For example, in a study by Peeters et al. (2014), French/English bilinguals had to switch between languages while additionally switching between a production and a perception task. Picture naming (i.e., the language-production task) was always in the same language, whereas the written words, on which the participants had to perform a language decision or semantic categorization task (i.e., the language reception task), switched between languages. As a more applied example, simultaneous interpreters can be considered to perform a very specific form of language switching as they perceive in one language and produce in a different language (e.g., Aparicio et al. 2017; De Groot and Christoffels 2006; Proverbio et al. 2004; Yudes et al. 2012).

Irrespective of whether language-perception or language-production tasks (or a combination thereof) are used, the most common empirical marker that is measured in language-switching studies are language-switch costs. Language-switch costs are calculated as the performance difference (in terms of reaction time [RT] or error rate) between language-switch trials, in which the target language in the current trial *n* is different from the target language in the previous trial *n*-1 (in Fig. 2 the first two "screens"/trials [trial *n*-2 to trial *n*-1] depict a language switch), and language-repetition trials, in which the relevant language in two successive trials is the same (in Fig. 2, the last two "screens"/trials [trial *n*-1 and trial *n*] depict a language repetition trial as the same language is relevant in these displays). A typical pattern shows worse performance (i.e., higher RTs and/or error rates) for language-switch trials than language-repetition trials and thus switch costs (e.g., Costa and Santesteban 2004; Declerck et al. 2012; Macizo et al. 2012; Meuter and Allport 1999; Gollan and Ferreira 2009).

Next to language-switch costs, mixing costs can also be measured in language-switching studies. Language-mixing costs are calculated as the performance difference between language-repetition trials in mixed-language blocks, in which participants switch between two languages, and language-repetition trials in single-language blocks, in which only one language is relevant across the whole block (although the target language typically switches between blocks). Results typically show worse performance in language-repetition trials in mixed-language blocks than in single-language blocks and thus language-mixing costs (e.g., Christoffels et al. 2007; Declerck et al. 2013; Peeters and Dijkstra 2018; Segal et al. 2019).

Language-switch costs and language-mixing costs are the two most widely used empirical markers in language-switching studies. On a theoretical level, the distinction between these two markers is interesting, as they are assumed to arise from separable mechanisms in language control. Language-switch costs are typically considered to be a marker for the fast adaption from one trial to the next. In this case, a language control mechanism is needed that solves between-language interference in each individual trial. Between-language interference presumably arises from (at least) two different sources: First, when switching between languages, the language(s) used in the previous trial(s) will influence performance in the current trial, creating between-language interference in case of a (recent) language switch. This applies for language-production tasks and language-perception tasks in a similar way. Second, when assuming a parallel activation of competing (translation-equivalent) lemmas in a language-production task, language control mechanisms are required to solve this interference and allow the selection of the correct lemma. In language-reception tasks, however, this source of between-language interference is less critical due to the bottom-up activation of the language by the language-specific stimulus. Nevertheless, in both types of tasks, between-language interference will arise and needs to be solved on a trial-to-trial basis. As this language control mechanism is reactive to the existence of between-language interference (i.e., if there was no between-language interference, no control mechanisms would be needed), it also referred to as *reactive language control*. We will further discuss the specific mechanism for reactive language control in Sect. 3 (What Language Switching Tells Us About Language Control).

In contrast to reactive language control, language-mixing costs resemble a proactive form of language control. Mixing costs are calculated as the performance difference in single-language blocks and mixed-language blocks. In the typology of Green and Abutalebi (2013), this resembles the difference between a single-language context and a dual-language context. In single-language blocks, only one language is relevant throughout the whole block, that is, either all stimuli have to be named in the same language (in language-production tasks) or all stimuli are presented in the same language (in a language-perception task). In mixed-language blocks, however, two different languages are potentially relevant so that participants need to be prepared to use either one of them. This global readiness to use either one language, however, is not (or only little) modulated from one trial to the next. Thus, language-mixing costs are presumably the result of a mechanisms of language control which enables participants to choose between languages. Although the language selection requirements are higher in language-production tasks than in language-perception tasks (due to the bottom-up activation in language-perception tasks), the global readiness to use one of two languages is similar in both types of languages tasks. Again, we will further discuss the specific mechanisms later on (see Sect. 3). First, we refer to different variants of the language-switching paradigm and describe the most common empirical findings as these provide the empirical evidence for any assumed language control mechanism.

2.2 *Different Variants of the Language-Switching Paradigm*

The most important distinction between different variants of the language-switching paradigm refers to the question as to whether language switching is mandatory or voluntary (cf. Jevtović et al. 2020; Gollan et al. 2014a). In mandatory language switching, the participant is told which language to use in a given trial by either a cue (e.g., a colored rectangle or a flag indicating the target language, e.g., Christoffels et al. 2007; Philipp et al. 2007) or by a specific trial sequence (alternating runs in which the language is switched every second trial; see, e.g., Declerck et al. 2013; Wong and Maurer 2021). In contrast, in voluntary language switching, participants can decide for themselves which language they are going to use in any trial (e.g., Gollan and Ferreira 2009; Gross and Kaushanskaya 2015).

Obviously, this distinction is mainly relevant for language-production tasks, in which participants need to decide which language to use. This decision is triggered exogenously in mandatory language switching (by either a cue or a predefined sequence) but endogenously by the participant in voluntary language switching. In contrast, in language-perception tasks, participants do not have to decide which language to use but the relevant language is indicated by the stimulus. While this entails that the language is activated bottom-up, whereas language activation is typically top-down in language-production tasks, language cues or a predefined language sequence can be used in language-perception tasks as well. For example, Jackson et al. (2004) let English natives that were familiar with either French, German, or Spanish perform a parity task based on visually presented number words (1–9, excluding 5). While it was not strictly necessary, an alternating language sequence was used (e.g., L1-L1-L2-L2-L1, etc.).

As the relevant language in language-perception tasks is indicated by the stimulus words (that are either spoken or written in one specific language), any additional language information is redundant. However, when presented before the actual target word, it could be used to prepare for the upcoming language. In the same way, in language-production tasks, presenting the language cues before the target stimulus allows participants to prepare for a specific language (e.g., Verhoef et al. 2009). Similarly, knowing the language sequence also provides the possibility to prepare for the upcoming language (e.g., Declerck et al. 2015a). Therefore, the possibility to prepare for the relevant language can be made comparable in language-production and language-perception tasks.

Nevertheless, as noted above, there is one critical difference between language-production and language-perception tasks during language switching. Whereas voluntary language switching can be realized for language-production tasks, this appears difficult in language-perception tasks due to the stimulus-based bottom-up activation of languages. However, this restriction mirrors real-life situations. Remember the two Spanish-Catalan bilinguals in the dense code-switching context. In such a situation, every speaker is free to choose which words to use – but the listener is not. This example already indicates that voluntary language switching can best be compared to the dense-code switching context (cf. Green and Abutalebi 2013) as participants can freely decide which language to use and when to switch to the other language. In contrast, mandatory language switching (and specifically cued language switching) is more comparable to the dual-language context as the relevant language is indicated by a cue. In an experimental setting, these cues can be relatively arbitrary (e.g., the color or the shape of a frame, e.g., Philipp et al. 2007). In a real-life dual-language context, the cue could be the person you are talking to (i.e., is it an English-speaking or a German-speaking colleague).

Taken together, we have already pointed out some similarities of all variants of the language-switching paradigm across language-production and language-perception tasks. Yet, we also identified important theoretical and methodological differences between language switching in language production and language perception. So, in the following sections, we will first review empirical findings regarding language switching using language-production tasks and then turn to empirical findings with language-perception tasks.

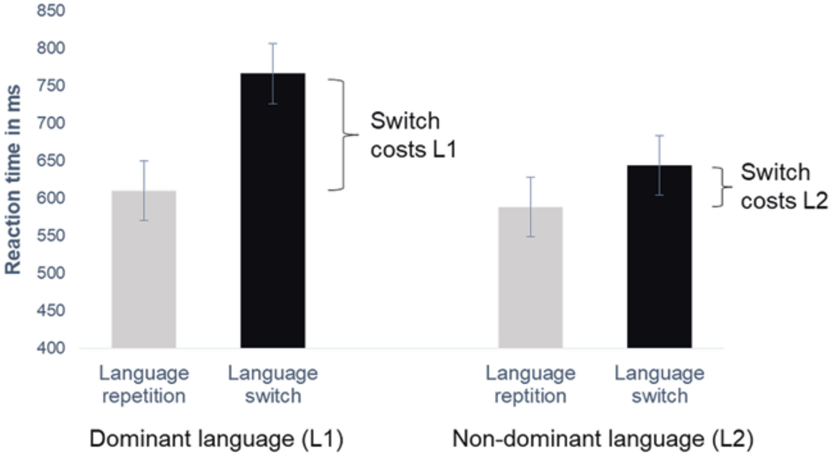
2.3 Typical Findings in Language Switching with Language-Production Tasks

When using language-production tasks, language-switch costs are typically observed across studies, regardless of the conditions of any specific experiment or the language-switching variant that has been used. More specifically, switch costs were found in cued language switching (Costa and Santesteban 2004; Christoffels et al. 2007; Meuter and Allport 1999), in language switching with predefined sequences (e.g., Declerck et al. 2013), and in voluntary language switching (Gollan and Ferreira 2009; Gross and Kaushanskaya 2015) – albeit language-switch costs tend to be smaller in voluntary language switching than in cued (i.e., mandatory) language switching (Jevtović et al. 2020). Although most studies used spoken responses only (i.e., vocally naming a picture or a digit), language-switch costs were also found in conditions in which participants responded manually by either handwriting (Wong and Maurer 2021) or by using a sign language for the naming response (e.g., Dias et al. 2017; Kaufmann and Philipp 2017).

Very few production studies have not found significant language-switch costs (e.g., Blanco-Elorrieta and Pylkkänen 2017; Declerck and Philipp 2015b; Kleinman and Gollan 2016). In line with the proposal of Blanco-Elorrieta and Pylkkänen (2018), most studies that do not show robust language-switch costs are more ecologically valid. For instance, Declerck and Philipp (2015b) found no language-switch costs in a sentence context when the word order was syntactically correct in both languages. Hence, in a more naturalistic setting, language-switch costs might be reduced to some degree. This might be an explanation why people, especially in a dense code-switching context, switch between languages – seemingly without a lot of costs – while experimental language-switching studies typically show costs of switching between languages. However, there is evidence that even in natural language, language switching or code switching is not free of costs (Fricke et al. 2016). Moreover, this is not in line with a recent study which showed that switch costs were larger in the context of sentences than during single-word production (Li and Gollan 2021). Hence, the influence of a sentence context on language control is not yet resolved.

Another finding that is frequently reported in the language control literature is the asymmetry of language-switch costs in language-production tasks (see Fig. 3), that is, in several language-switching studies, participants had larger language switch costs for the more dominant language compared to the less dominant language (e.g., Philipp et al. 2007; Meuter and Allport 1999). In the study by Philipp et al. (2007), the switch costs were larger for L1 than for L2 when participants switched between L1 and L2. In a L2/L3 switching condition, switch costs were larger for L2 than for L3.

However, a language switch-cost asymmetry does not occur in all studies. While some studies show this pattern (e.g., Kaufmann et al. 2018; Meuter and Allport 1999; Reynolds et al. 2016), others find no asymmetrical switch costs (e.g., Finkbeiner et al. 2006; Peeters and Dijkstra 2018), or a reversed asymmetrical switch-cost pattern (e.g., Bonfieni et al. 2019; Declerck et al. 2015b). Regarding studies that do not observe asymmetrical switch costs, some of these studies relied on highly proficient bilinguals (e.g., Costa and Santesteban 2004; Costa et al. 2006). As these bilinguals should have a similar language dominance in both languages, no difference should be expected between L1 and L2 switch costs (in terms of the size of switch costs) for these bilinguals. However, highly proficient bilinguals have also shown symmetrical switch costs when switching between L1 and a less proficient



Note: Idealized reaction times (in ms) as a function of language transition (language repetition vs. language switch) and relevant language in the current trial (dominant vs. non-dominant language). The figure shows an asymmetry of language-switch costs with larger switch costs in L1 than in L2 and a reversed dominance effect with an overall better performance in the non-dominant language L2 than in the dominant language L1.

Fig. 3 Idealized data pattern in a language-switching experiment
Note: Idealized reaction times (in ms) as a function of language transition (language repetition vs. language switch) and relevant language in the current trial (dominant vs. non-dominant language). The figure shows an asymmetry of language-switch costs with larger switch costs in L1 than in L2 and a reversed dominance effect with an overall better performance in the non-dominant language L2 than in the dominant language L1

L3 (Costa and Santesteban 2004), which cannot be explained with a similar dominance between languages. Along the same lines, several studies with second-language learners also showed no asymmetrical switch costs. Hence, the robustness of this measure has been put into question (e.g., Bobb and Wodniecka 2013). Further, as regards the observation of a switch-cost asymmetry, there was not only a difference between participants but also a difference between language-switching paradigms. Whereas an asymmetric switch-cost pattern was often (albeit not always) observed in cued language-switching studies, it rarely occurred in voluntary language switching (Gollan and Fereirra 2009). Yet, a meta-analysis on 73 language-switching studies (Gade et al. 2021) indicated that asymmetric switch costs are not always present, even in cued language-switching studies with L2 learners. Thus, although quite a number of studies observed asymmetrical language-switch costs, it is not yet clear which factors modulate such an asymmetry and under which conditions the asymmetry is most likely found.

Another measure that has been relatively consistently observed across language-switching studies that rely on a production task are mixing costs, that is, slower responses and more errors in mixed than in pure language blocks (e.g., Christoffels et al. 2007; Declerck et al. 2013; Stasenko et al. 2017). The only exception to this rule are voluntary language-switching studies. These studies either show an L2 mixing benefit (e.g., Gollan and Ferreira 2009; Gross and Kaushanskaya 2015) or an overall language-mixing benefit (e.g., De Bruin et al. 2018, 2020; Grunden et al. 2020; Jevtović et al. 2020).

As language-switch costs, language-mixing costs (if present) tend to be asymmetrical with a larger mixing cost in the dominant language relative to the non-dominant language (Christoffels et al. 2007; Declerck et al. 2020b). In turn, there can be a L1 performance benefit over L2 in single language blocks that is reversed in mixed language blocks. Other studies that did not include single language blocks also reported worse performance of L1 compared to L2 in mixed language blocks, indicating a "reversed dominance effect" (Peeters and Dijkstra 2018; for a review see Declerck 2020; for an idealized visualization of the reversed dominance effect, see Fig. 3). Yet, the data pattern concerning a reversed dominance effect is far from being conclusive as there are also a multitude of studies that found an overall better performance in L1 than in L2, even in mixed language blocks (Ma et al. 2016; Wang et al. 2009). Correspondingly, as for asymmetric switch costs, the meta-analysis provided by Gade and colleagues (2021) also found no clear empirical support for a consistent occurrence of the reversed dominance effect in the literature. Therefore, more research is needed to further determine the boundary conditions for the occurrence of a (reversed) dominance effect.

Taken together, the most important findings in language switching using language-production tasks comprise the observation of (asymmetrical) language-switching costs, language-mixing costs, and a reversed language dominance effect. If there was a difference of these measures between languages, both switch costs and mixing costs were larger for the dominant than for the non-dominant language, leading to an asymmetry in the data pattern.

2.4 Typical Findings in Language Switching with Language-Perception Tasks

Language-switching studies with language-perception tasks tend to show most of the language-switching effects reported above. However, the effects tend to be less robust across studies than in language-switching studies using production tasks. One prominent example is that of language-switch costs. This pattern has been observed in several language-switching studies that used perception tasks, in which participants had to categorize words based on, for instance, their lexicality (e.g., word vs. nonword; e.g., Ong et al. 2019; Struck and Jiang 2021) or semantic characteristics (e.g., animate vs. inanimate; e.g., Macizo et al. 2012; Struys et al. 2019). However, in many studies, switch costs were only observed in certain conditions (e.g., Declerck and Grainger 2017; Jackson et al. 2004; Orfanidou and Sumner 2005; Von Studnitz and Green 2002). For instance, several studies observed a switch benefit when a different manual response had to be given on the current trial relative to the previous trial (e.g., Orfinadou and Sumner 2005; Von Studnitz and Green 2002). Moreover, in a recent, comprehensive study, Declerck et al. (2019b) observed no language-switch costs when French/English or French/Spanish bilinguals performed a magnitude, parity, or animacy task across seven experiments. Moreover, even a combined dataset across all seven experiments did not show language-switch costs.

In turn, asymmetrical switch costs are also not robust when using language-perception tasks. That does not mean that such a pattern is never observed (e.g., Jackson et al. 2004). In the study of Mosca and de Bot (2017), Dutch/English bilinguals were given a lexical decision task in mixed language blocks. The results showed asymmetrical switch costs, but only when the responses were repeated, whereas symmetrical switch costs occurred when a different response was required across two trials. However, other language-switching studies that used language-perception tasks did not observe asymmetrical switch costs at all (e.g., Jylkkä et al. 2018a; Von Studnitz and Green 2002) or found a reversed asymmetrical switch-cost pattern (i.e., larger L2 than L1 switch costs; e.g., Liu et al. 2020; Struck and Jiang 2021). So, similar to overall language-switch costs, asymmetrical switch costs are not very robust in the context of language perception.

Unlike switch costs and their asymmetry, only a handful of studies have examined mixing costs with language-perception tasks. In the study of Grainger and Beauvillain (1987), French/English bilinguals performed a lexical decision task in mixed and single language blocks. No mixing costs were observed. In the more recent paper by Declerck et al. (2019b), mixing costs were investigated with French/English and French/Spanish bilinguals using a variety of tasks in three experiments. Language-mixing costs were only observed with French/Spanish bilinguals. The authors argued that this was due to the large phonological overlap between the French words and their translation-equivalent Spanish words, which was much smaller between French and English. Consequently, more interference had to be resolved, which resulted in substantial language-mixing costs.

As there is little research on mixing costs in language switching using perception tasks, we cannot draw any conclusions on a potential asymmetry of mixing costs in language-perception tasks. Similarly, with respect to a (reversed) language dominance effect, there is no conclusive pattern of results across studies. If at all, however, studies point toward a regular dominance effect with a better performance in trials in which a L1 target stimulus is presented than in trials in which L2 is presented (e.g., Hirsch et al. 2015; Macizo et al. 2012; Struck and Jiang 2021).

To summarize the most important findings in language switching using a language-perception task, it appears that only language switch costs can be observed in many – albeit not all – studies. As regards switch-cost asymmetries, mixing costs (and their asymmetry), and the reversed language dominance effect, very little evidence is provided in language switching using language-perception tasks.

2.5 *Empirical Differences in Language Production vs. Perception*

As we have reviewed in the previous two sections, language-switch costs can be observed in language-production and language-perception tasks. Yet, asymmetrical switch costs are typically found with language-production tasks, but not with language-perception tasks. Further, (asymmetric) mixing costs and a reversed language dominance effect are also frequently reported in language-switching studies using language-production tasks but rarely in studies using language-perception tasks.

A further difference in language switching studies using production vs. perception tasks refers to modality-specific effects. Modality-specific effects can occur when participants switch between two languages that either use different output modalities in case of language-production tasks (e.g., switching between vocal responses in German and manual responses in German sign language, e.g., Kaufmann et al. 2018; Schaeffner et al. 2017) or use different input modalities in the case of language-perception tasks (e.g., Schaeffner and Philipp 2020). In such a bimodal language-switching situation, Kaufmann et al. (2018) found that language-switch costs were smaller in bimodal switching as compared to a unimodal switching (i.e., switching between vocal responses in either German or English). Interestingly, Schaeffner et al. (2017) could further demonstrate that the bimodal advantage only referred to switching between a spoken and a sign language. When switching between vocal responses in German and typed responses in English or French, no such bimodal advantage occurred. In contrast, language-switching studies using language-perception tasks resulted in larger bimodal switch costs compared to a unimodal situation (Schaeffner and Philipp 2020), that is, switching between hearing stimulus words in one language and seeing stimulus words in the other language led to higher switch costs than switching between hearing the stimulus words in one language and hearing them in the other language (i.e., all stimulus words were presented auditorily). Taken together, assigning the two languages to distinct modalities resulted in a switch-cost increase in language-perception tasks but to either no effect or a switch-cost decrease in language-production tasks.

In the next section, we will discuss these empirical findings with respect to theories and models of bilingual language control. The important theoretical question hereby will be whether language control in production and perception tasks is governed by comparable mechanisms.

3 What Language Switching Tells Us About Bilingual Language Control

In previous sections, we have focused mainly on three effects – (asymmetrical) language-switch costs, language-mixing costs, and the reversed language dominance effect. However, language-switch costs on the one side and language-mixing costs and the reversed language dominance effect on the other side are markers of different language control processes, namely, reactive and proactive language control, respectively. Thus, when discussing language control in language switching studies using either language-production or language-perception tasks, we first focus on reactive language control and then focus on proactive language control and a possible interplay of reactive and proactive language control.

3.1 Reactive Language Control in Bilingual Language Production vs. Perception

In models on language production as well as in models of language perception, language non-selectivity is assumed (Green 1998; Grainger et al. 2010). In turn, parallel activation of languages can occur, which was demonstrated for language-production studies (e.g., De Groot et al. 2000) and language-perception studies (e.g., Dijkstra et al. 2000; Shook and Marian 2013). Whenever the performance of participants requires the selective attention to one but not the other language, for example, when being asked to name an object in the language indicted by the cue, the parallel activation of languages results in between-language interference. In order to perform a specific task, participants, thus, make use of reactive language control – which in most cases is assumed to be inhibitory language control (e.g., Green 1998), that is, the non-target language is assumed to be inhibited to resolve the between-language interference (cf. Green 1998; Declerck et al. 2015a). This form of language control is referred to as reactive, as it acts upon the presence of between-language interference.

In language switching with language-production tasks, language-switch costs are typically explained by reactive language control (see Sect. 1.2 of this chapter for a discussion). Further, the switch-cost asymmetry is often taken as an additional empirical marker for reactive inhibition (cf. the ICM of Green 1998): the more the non-target language is interfering with the target language, the stronger it has to be inhibited. When a stimulus is presented in language-production tasks, this stimulus will activate the translation-equivalent lemmas in both languages. Yet, a larger activation can be expected in the more dominant language than in the non-dominant language (cf. Kroll and Stewart 1994). Thus, the dominant language needs to be inhibited very strongly to allow for the selection of the lemma in the non-dominant language. In contrast, less inhibition of the non-dominant language is necessary to produce a word in the dominant language. As this inhibition persists into the next trial(s), it will take more time to switch back to the strongly inhibited dominant language than to switch back to a less strongly inhibited non-dominant language, leading to the switch-cost asymmetry. Yet, as noted above, the switch-cost asymmetry was not always found and thus, still, is a matter of debate (cf. Bobb and Wodniecka 2013; Gade et al. 2021).

In comparison to language-production tasks, language-switch costs were less consistently observed in when using language-perception tasks. Further, if language-switch costs were present, they were not asymmetrical between the two languages (e.g., Jylkkä et al. 2018a; Macizo et al. 2012; but see Mosca and de Bot 2017, for asymmetrical switch costs in a language-perception task). In terms of inhibitory language control, Grainger et al. (2010) argued that inhibitory language control also plays a role in language switching using language-perception tasks. Yet, language control in language-perception tasks will be triggered exogenously by the language-specific stimuli (i.e., a word presented in German will activate the German language node and in turn language nodes of other languages will be inhibited). Although there is a difference in the trigger mechanisms of language control (endogenous in language-production tasks and exogenous in language-perception tasks), Grainger et al. (2010) proposed a similar inhibitory language control in production and perception tasks.

If inhibitory language control relies on the same underlying language control system in language production and language perception, as argued by Grainger et al. (2010), language-switch costs should also be observed when switching languages across production and perception tasks. In a study by Gambi and Hartsuiker (2016), two participants took part in a language-switching experiment together and had to perform a naming task. As both participants responded in turn, the production trial of one participant also was a perception trial for the other participant. While one of the participants switched between two languages, the other participant used the same language in all trials. Nevertheless, the participant using only one language showed a language-switch costs depending on whether the other participant had used the same language in the previous trial (i.e., language-repetition trial across perception and production) or had used the other language (i.e., language-switch trial). Similarly, results of Peeters et al. (2014) showed switch costs across production and perception when each participant performed in a production and a perception task in turn. Furthermore, in this study, asymmetrical switch costs were observed during production. Put differently, when participants had to perform a perception task, this had an influence on the following production task.

There is further evidence pointing toward similar control mechanisms in language switching using language-perception and language-production tasks. More specifically, practicing one of the languages before the experiment affected the switch-cost asymmetry in both variants of language switching. When using a language-perception task, Declerck and Grainger (2017) were able to demonstrate that practicing the dominant language before the experiment led to the occurrence of asymmetrical language-switch costs. Similarly, Declerck and Philipp (2017) showed that practicing the non-dominant language before a language-production experiment reduced the switch-cost asymmetry between the dominant and the non-dominant language. Although there are important empirical differences in the results of both studies (e.g., while Declerck and Philipp 2017 found an influence of recent practice of the non-dominant language, practicing the non-dominant language had no effect in the study of Declerck and Grainger 2017), these experiments support the idea that reactive, inhibitory language control is at work in language switching and that the dominance of the languages (which was manipulated by recent practice) influences language control.

Despite such evidence supporting common mechanisms in reactive language control between language-production and language-perception tasks, a number of studies demonstrate substantial differences in language control between production and perception tasks. For example, an eye-movement study by Ahn et al. (2020) directly compared language switching with a language-production task (reading aloud) and a language-perception task (silent reading) and observed distinct data pattern across both types of task switching (see also Macizo et al. 2012, and Mosca and de Bot 2017, for studies including both production and perception tasks in language switching). Further, also the pattern of neuronal activation between language-production and language-perception tasks was observed to be different in magnetoencephalography (MEG) studies (Blanco-Elorrieta and Pylkännen 2016, 2017).

Some of the empirical differences observed in language switching between language perception and language production hereby may be due to methodological differences. For example, one such difference is that during perception studies, typically language-specific stimuli (e.g., written words) are implemented, whereas production studies generally use language-unspecific stimuli (e.g., digits and pictures). Put differently, in language-perception tasks the stimulus is language-specific but the response (i.e., key press) is language-unspecific, and in language-production tasks the stimulus is language-unspecific but the response is language-specific (see Fig. 2). This could be important, since an (un-)specificity on the stimulus and/or response side is known to affect the relative size of performance costs (cf. Finkbeiner et al. 2006; for a similar discussion in task switching, see Meiran 2000). Thus, one might argue that empirical differences like the occurrence of asymmetrical switch costs (which is more often observed in language-production than in language-perception tasks) can be explained by stimuli and/or responses being language-specific vs. language-unspecific. Yet, Reynolds et al. (2016) showed a switch-cost asymmetry in a language-production tasks even when language-specific stimuli (i.e., number words) were used (see also Slevc et al. 2016).

One aspect that is related to the language (un-)specificity of responses is the issue of response congruence, that is, in language-perception tasks, the response is language-unspecific as each key press in a categorization task (e.g., animate categorization) has a meaning for both languages. However, the target word *Hund* in German would be classified as animate in the same way as its translation-equivalent English word *dog*. Thus, the co-activation of translation-equivalent lemmas would not lead to a response conflict (cf. Macizo et al. 2012). Yet, this is not the case in all language-perception tasks. For example, von Studnitz and Green (1997) asked participants to decide whether a target stimulus was a word or a non-word (i.e., lexical decision task). Language-switch costs emerged irrespective of whether the non-words had to be categorized in a language-specific (i.e., is it a non-word in English) or a language-unspecific way (i.e., is the stimulus a word vs. non-word in any language). In a language-specific condition, the word/non-word decision might be different between languages so that responses are not per se congruent (i.e., a string of letters might be a word in English but a non-word in German). Thus, there might be difference between language control in the language-specific and in the language-unspecific condition. However, please note that the study of von Studnitz and Green (1997) did not use non-words that might be words in the other language. Rather, non-words were constructed in a way that they were orthographically legal in either both languages or in only the target language. Nevertheless, von Studnitz and Green (1997) observed larger language-switch costs in the language-specific than in the language-unspecific condition.

The examples reported in the previous two paragraphs already indicate that differences in the type of stimuli and responses go along with a difference in the language-related task that participants need to perform within the experiment. In perception studies, different tasks have been used across studies, ranging from a lexical decision (e.g., word vs. non-word decision) to categorization tasks (e.g., living vs. nonliving decision). In production studies, the task typically consists of vocally naming a stimulus (i.e., digit or picture) or reading aloud. These different types of tasks might also affect the language control processes differently.

In a language-switching study by Declerck and Philipp (2018), both the stimulus type and the task were taken into account. However, the study did not examine language-switch costs but n-2 repetition costs. N-2 repetition costs can be measured when participants switch among three languages (e.g., Philipp et al. 2007; Philipp and Koch 2009; Timmer et al. 2018) and represent the performance difference between n-2 language repetitions (e.g., a trial sequence like L2, L1, L2) and n-2 language switches (e.g., a trial sequence like L3, L1, L2). N-2 repetition costs are interpreted as a marker of reactive, inhibitory language control as the worse performance on the last trial in a n-2 language repetition sequence is attributed to a performance cost when switching back to a recently inhibited language. More specifically, when switching from L2 to L1 (the first two trials in the sequence L2, L1, L2), the recently activated but now irrelevant language L2 will become inhibited (i.e., reactive inhibition). As the inhibition persists into the next trial (in the example the last trial in the sequence L2, L1, L2), switching back to L2 suffers from L2 still being inhibited. In contrast, switching to L2 in a task sequence like L3, L1, L2 should lead to less of a performance decrease as there is less persisting inhibition on L2 because L2 was inhibited far longer ago. Declerck and Philipp (2018) had participants switch between three languages (German, English, and French) in four different conditions. One was a standard picture-naming condition (language-production task with language-unspecific stimuli), the second was a word-reading condition (language-production task with language-specific stimuli), the third was a picture categorization task (i.e., does the word corresponding to the visually presented object contain the letter L or S, language-perception task with language-unspecific stimuli), and the fourth condition was a word categorization task (language-perception task with language-specific stimuli). The results showed n-2 repetition costs in both language-production tasks but not in language-perception tasks (to be precise, n-2 repetition costs in language-perception tasks occurred only in the least dominant language, French, in the picture-categorization task but not in the other languages or the word-categorization task). These results are in line with studies on language-switch costs (Reynolds et al. 2016; Slevc et al. 2016) that showed switch costs in language-production tasks also in conditions with language-specific conditions. Further the results again demonstrate that inhibitory language control is presumably stronger in language-production than in language-perception tasks.

When taking a closer look at the results of Declerck and Philipp (2018), one can see that the n-2 repetition costs in the word-reading condition were relatively small (i.e., 6 ms only). The authors concluded that the type of task might have played a role here as less lexical selection is necessary in a word-reading task, whereas lexical selection is more critical in picture naming. In fact, models of language control in bilingual language production (Declerck et al. 2015a; Green 1998) assume that between-language interference and language control at the level of lexical selection are important in language switching (see also Finkbeiner et al. 2006).

Yet, language control at the level of lexical selection is certainly not the only level in language processing at which language control can be located. Thus, one also needs to consider that inhibitory processes take place at different levels in language processing (i.e., multiple stages of language control, cf. Kroll et al. 2006). Put differently, it could be assumed that production-based and perception-based language control overlap in one or more of these stages, but not in others. Different models of language control already assume slightly different levels of language control. Whereas Green (1998) argued for language control mainly at the level of language schemas (i.e., a representation of the action requirements like “name a picture in English”) and between translation-equivalent lemmas (i.e., on the level of lexical selection), Declerck et al. (2015a) argued in favor of language control at the level of language nodes and lemmas. Language nodes are also assumed to play a critical role in language control in the perception-based model of Grainger et al. (2010). Further, Schaeffner et al. (2017) argued that the reduction of language-switch costs in bimodal language switching compared to unimodal language switching could be attributed to a different level of language control. While lexical selection remains the critical level in unimodal language switching, two lemmas can remain activated in bimodal language switching (i.e., there is no/less need to resolve language interference by reactive inhibition at the lemma level). Rather, in bimodal switching, inhibitory language control is possible on the level of output modalities (vocal output vs. manual output; see also Declerck et al., 2021a, b; Kaufmann et al. 2018).

Finally, a potential influence of a phonological or orthographic overlap between translation-equivalent lemmas in both languages is effective at different points in time in language switching using language-production or language-perception tasks. In production-based language switching, it is effective only after lemma selection but may influence lemma selection by feedback loops (Declerck and Philipp 2015c). In contrast, in perception-based language switching, phonological or orthographic overlap can become relevant before the activation and selection of the correct lemma. Similarly, different input modalities have its influence before lemma selection and language node activation in perception-based language switching, while output modalities come into play only after lemma selection in production-based language switching.

To summarize, there is some evidence that lexical selection plays a critical role in the occurrence of (asymmetric) language switch costs. Put differently, we can assume that language-switch costs (as a marker of reactive language control) are at least partially due to the resolution of interference on the level of lemma selection (i.e., overcoming the persisting inhibition of a recently inhibited language and activating the correct language). However, it could be argued that interference (and, thus also the need to resolve this interference by reactive, inhibitory language control) is reduced when:

1. The lemma is activated exogenously by the presentation of a target word as in language-perception tasks.
2. The translation-equivalent lemma could remain activated as the responses are congruent for both languages as in classification tasks (e.g., animacy decision in language-perception tasks; cf. Macizo et al. 2012).
3. When there is no/less need for interference resolution because language control occurs on a later level (as in bimodal switching; see Schaeffner et al. 2017).
4. When there is no restriction on lexical selection as both lemmas could be selected as in voluntary language switching (see Gollan and Ferreira 2009).

In such (and probably other) cases, a reduced reactive language control results in a smaller amount of persisting inhibition so that switching back to the previously irrelevant language becomes less effortful – which on the empirical level results in smaller switch costs.

3.2 Proactive Language Control in Bilingual Language Production vs. Perception

In contrast to reactive language control that comes into play to resolve between-language interference, proactive language is assumed to prevent between-language interference prior to its occurrence (cf. Declerck 2020). The general idea here is that the potential conflict between languages triggers control mechanisms that work against the occurrence of such interference.

When we consider language-mixing costs, one component of proactive language control refers to the overall readiness to switch between languages. More specifically, in a pure language block, only one of two (or more) languages is relevant so that there it is, on the one hand, perfect predictability and, on the other hand, no need to change (and to monitor) the activation of that one language on a trial-to trial basis. In general, this will lead to less language control so that overall performance is better in pure language blocks than in in mixed language blocks. Correspondingly, language-mixing costs occur (e.g., Christoffels et al. 2007).

However, this is only the case in a dual-language context or cued language switching, respectively. In a dense-code switching context, there is no need to control the language used in a given trial. Rather, the first language response that is ready can be used. Accordingly, de Bruin et al. (2018) argued that the language-mixing benefit in voluntary language switching (i.e., better performance in mixed language blocks than in pure language blocks) is due to pure language blocks relying on proactive language control on the non-target language (for a review, see Declerck 2020). No such control processes are necessary in voluntary mixed language blocks, since the bilingual participants can freely choose which language to use for each target stimulus. As the usage of proactive control process is cognitively demanding, worse performance is expected in single language blocks than in voluntary mixed language blocks.

A second aspect of proactive language control that was argued to play a role in mixed language blocks is a global inhibition of the dominant language (cf. Christoffels et al. 2007; Declerck et al. 2020b; for a review see Christoffels et al. 2016). Switching between languages might be most effective when the dominance difference is relatively low. A small dominance difference, for example, could prevent premature responses in the dominant language (see, e.g., Finkbeiner et al. 2006). A way of creating an overall similar activation level for both languages could be a global suppression/inhibition of the dominant language. Yet, adjusting the activation level of a language is certainly difficult so that the global inhibition of L1 might be not enough or too strong in some cases. When the global inhibition of L1 was too strong, the performance in L1 in the mixed language blocks might even be worse than the performance in L2, resulting in a reversed language dominance effect. The difficulty in the perfect adjustment of language activation in mixed language blocks also explains why a reversed language dominance effect is observed in some studies but not in all studies (see the meta-analysis of Gade et al. 2021). Further, as the activation of languages (i.e., language nodes) is endogenously in language-production tasks only, this also explains why mixing costs and a reversed dominance effect are mainly observed in language switching studies with language-production tasks. If there was an exogenous activation of language nodes, proactive language control might be less effective compared to the exogenous, stimulus-based activation of languages.

3.3 Interplay of Reactive and Proactive Language Control

Quite some research has indicated that the two processes of reactive and proactive language control are distinguishable (e.g., Christoffels et al. 2007; Declerck et al. 2013; Ma et al. 2016; Prior and Gollan 2011; Stasenko et al. 2017). For instance, Ma et al. (2016) observed an effect of the response-to-cue time on language-switch costs, possibly indicating that reactive language control relies on passive decay, whereas that was not the case for language-mixing costs.

While these different aspects of language control might be distinguishable control processes, it has been suggested that they might actually work in unison (Declerck 2020), as they both have the same goal (i.e., ease bilingual language production through diminishing cross-language interference). It could, for example, be that circumstances with a high level of proactive language control do not require a high level of reactive language control, since there will be relatively less cross-language interference. If this was the case, there should be a negative correlation between a reversed language dominance effect (indicating proactive language control) and asymmetric switch costs (indicating reactive language control). Such correlation was calculated in the meta-analysis of Gade et al. (2021) but revealed only a nonsignificant negative correlation of $r = -0.12$. Yet, as neither the reversed language dominance effect nor asymmetric switch costs could be supported by the models in the meta-analysis, this non-significance should be treated with caution. More research is certainly required to confirm this claim.

4 Is Language Multitasking a Specific Form of Multitasking?

In order to answer the question whether language multitasking is a specific form of multitasking (or whether language switching is a specific form of task switching), one can look at several different aspects. At first, we focus on studies that directly compared language switching and task switching. Then, we review studies in which an overlap between language switching and other forms of multitasking is explored, including the discussion as to whether life-long bilingualism provides a general advantage for other forms of cognitive control and multitasking. In the end, we will point out some possible future directions of multitasking research that could be derived from language multitasking.

4.1 Language Switching and Task Switching

Whereas participants switch between two languages in the language-switching paradigm, participants switch between two tasks in the task-switching paradigm (for reviews, see Kiesel et al. 2010; Koch et al. 2018). For example, in the seminal study of Rogers and Monsell (1995), participants had to decide whether a digit was odd or even in one task and whether a letter was a vowel or a consonant in the other task. A standard finding in the task switching literature is the occurrence of task-switch costs, which can be calculated as the performance difference between task-switch trials and task-repetition trials.

In a number of studies, participants performed both language-switching (using a language-production, i.e., naming, task) and task-switching experiments (e.g., Branzi et al. 2016a; Calabria et al. 2015; Declerck et al. 2017a; Klecha 2013; Prior and Gollan 2013; Timmer et al. 2018). In such studies, the size of language-switch costs and the size of task-switch costs can be correlated. If language switching and task switching relied on similar control mechanisms and resembled the same form of sequential multitasking, there should be a substantial correlation between language-switch costs and task-switch costs. Indeed, some studies demonstrated significant correlations (Declerck et al. 2017a; Timmer et al. 2018). Yet, most studies found correlations only in some conditions or observed a weak correlation only (Branzi et al. 2016a; Klecha 2013; Prior and Gollan 2013). To interpret these results, one also has to keep in mind that even when correlating one language-switching condition with another language-switching condition, reliability scores are only at a medium range (Contreras-Saavedra et al. 2021a; Timmer et al. 2018).

In this context, the study of Declerck et al. (2017a; see also Declerck et al. 2021b) is of specific interest. In this study, task-switching requirements were gradually changed to better match the language-switching paradigm used in this study. Typical differences between task-switching studies and language-switching studies usually affect the nature of stimuli, the number of responses, and the response modality. Regarding response-related aspects, task-switching studies typically imply two manual key-press responses (where the same response keys are used for both tasks and, thus, have a different meaning in each task task), while language-switching studies imply a large number of language-specific vocal naming responses. This is because most task-switching studies use stimulus classification tasks (e.g., perceptual categorizations like color categorization [is a stimulus red or blue] vs. form categorization [is a stimulus a circle or a square] or numerical categorizations like a magnitude [is a number smaller or larger than 5] vs. a parity decision [is a number odd or even]). In contrast, language-switching studies typically use a naming task (i.e., a language-production task). Based on the distinction between language switching in language-production tasks and language-perception tasks, one could thus argue that correlations between task switching and language switching are typically conducted between two different types of tasks (see, e.g., Timmer et al. 2018). Put differently, the tasks used in task switching would more closely resemble language-perception tasks. As we already summarized a considerable amount of differences in the language control mechanisms between language-production and language-perception tasks, it is no surprise to also observe differences between task switching and languages switching. Interestingly, in the study of Declerck et al. (2017a), the size of language-switch costs and task-switch costs became more similar (and the correlation increased) when not only the response modality (i.e., verbal responses), the number of responses, and the target stimuli were identical across language switching and task switching but also the task that had to be performed (e.g., a numerical categorization task).

A potential overlap in control mechanisms between language control and cognitive control might also be reflected in studies that explored the neural activation patterns in either language or cognitive control tasks. A number of studies showed that language control and cognitive control at least partially activate the same neural networks (see, e.g., Branzi et al., 2016b; De Baene et al. 2015; De Bruin et al. 2014; Calabria et al. 2018; Weissberger et al. 2015). Further, the neural activation pattern seems to depend on language proficiency (Abutalebi et al. 2013) and the overlap between language and cognitive control appears to be present mainly in bilinguals as compared to monolinguals (see Anderson et al. 2018; Coderre et al. 2016; Timmer et al. 2017). In a study by De Baene et al. (2015), the same participants (highly proficient bilinguals) performed both a language-switching and a task-switching condition. An fMRI analysis comparing both conditions (conjunction analysis) revealed a large neural network that was active in both types of switching. Further analyses (disjunction analyses) also revealed brain areas that differed in activation between language switching and task switching. Yet, it is important to point out that even when comparing two different types of task switching (i.e., stimulus-categorization switching and response-modality switching; see Philipp et al. 2013), the pattern of neural activations demonstrates both a partial overlap in the neural activation across both types of task switching and specific differences.

Finally, while there is both evidence for and against a domain general language control process in the production literature, the evidence in the perception literature is more slim but also more straightforward. Several studies have shown no relationship between language switching and task switching (Jylkkä et al. 2018a; Struck and Jiang 2021) or another non-linguistic measure of cognitive control (e.g., flanker task; Declerck et al. 2019a; Struys et al. 2019). Hence, it seems like there is little to domain generality of language control during bilingual language perception.

4.2 Language Switching and Cognitive Control in General

Next to directly comparing language switching and task switching, one can also explore whether there is an overlap between language switching and other paradigms measuring cognitive control (e.g., Jylkkä et al. 2018b; Segal et al. 2019). In a study by Segal et al. (2019), language switching was not set into comparison with task switching but also with a flanker task, in which inhibitory control is also assumed to be relevant. In a flanker task, participants have to react to a central stimulus (e.g., an arrow pointing to the left side) and ignore surrounding stimuli (e.g., arrows pointing to the left side). In order to be able to respond correctly to the central stimulus, the processing of the (irrelevant) surrounding stimuli has to be inhibited (cf. Verbruggen et al. 2006). When we compare performance in the flanker task with language-switching performance, it becomes apparent that it is more closely related to language switching with language-perception tasks as the stimulus can exogenously activate the correct response (e.g., an arrow pointing to the right activates a right-sided key press). Yet, in contrast to language-switching studies using a language-perception task, the surrounding flankers can lead to an incongruent response activation, whereas the translation-equivalent lemma in perception tasks will typically activate the same response (e.g., in an animate decision task, cf. Macizo et al. 2012). In the study of Segal et al. (2019), the flanker task, however, was compared to a language-switching using a language-production task (i.e., digit naming). Consequently, the study also reported differences between control mechanisms in language switching and the flanker task. Jylkkä and colleagues explored a possible relationship of the flanker task not only to language switching using a language-production task (Jyllkä et al. 2018b) but also to language switching using a language-perception task (Jylkkä et al. 2018a; see also Declerck et al. 2019a). Nevertheless, the results were inconsistent in both studies, demonstrating some overlap but also critical empirical differences in the pattern of results.

However, most research interest on the question of a relationship between language switching and general cognitive control was focused on the question whether bilinguals can outperform monolinguals in cognitive control tasks due to their lifelong practice in dealing with cross-language interference. The idea that monolinguals and bilinguals differ in terms of their cognitive abilities is not new as it was already explored by Peal and Lambert (1962; please note that this study refers to even older studies from the 1920s that already addressed this question) who argued that monolinguals and bilinguals should differ in the intellectual abilities and indeed demonstrated a benefit of bilinguals relative to monolinguals in different verbal and nonverbal intelligence measures.

During the last two decades, an incredible number of studies compared monolinguals and bilinguals in different cognitive control tasks like task switching (e.g., Hernández et al. 2013; Prior and MacWhinney 2010; Wiseheart et al. 2016), the flanker task (e.g., Costa et al. 2009; Ong et al. 2017), Stroop tasks (e.g., Blumenfeld and Marian 2014; Coderre et al. 2013; Sabourin and Vīnerte 2015), or the Simon task (e.g., Bialystok et al. 2004; Blumenfeld and Marian 2014). While several studies were able to demonstrate a bilingual advantage (i.e., a better performance of bilinguals as compared to monolinguals in cognitive control tasks; for reviews see Bialystok 2017; Valian 2015), the evidence for a bilingual advantage was also put into question (see, e.g., Paap and Greenberg 2013). Additionally, several meta-analyses on the bilingual advantage provide only weak to no evidence in favor of a systematic and general bilingual advantage (Donnelly et al. 2019; Lehtonen et al. 2018). Again, characteristics of the participants (including the age of the participants; for a discussion see Antoniou 2019), methodological differences between paradigms and between studies, and many other factors influence the specific data pattern observed in each study (for a review, see Van den Noort et al. 2019). Consequently, a number of researchers suggested to move beyond the discussion of a general bilingual advantage and turn to, for instance, advantages in real life (cf. Poarch and Krott 2019).

4.3 What Can We Learn from Language Multitasking

In the previous sections, we have reviewed numerous studies that, in one way or another, contribute to the discussion whether language multitasking is qualitatively different from other forms of multitasking or whether it can be subsumed under the general term of multitasking without losing important information. However, it became apparent that this question cannot be solved, at present. Empirical studies provided evidence that there are a large number of similarities (both on the behavioral and the neural level) but there are also considerable differences.

In some ways, the question about potential differences in (language) multitasking could be compared to other questions about differences like the question whether there are differences between women and men. On the one hand, the answer to this question appears easy as there certainly are differences between women and men (e.g., when looking at the level of chromosomes). On the other hand, when looking specifically at individual aspects, the answer is not so clear anymore. For example, men tend to have a larger body height than women. Yet the differences within the group of men are also huge so that there are certainly a lot of cases in which an individual woman is larger than a man.

Similarly, the differences in empirical measures (e.g., size of switch costs, asymmetry of switch costs) within the field of language switching are huge (cf. Gade et al. 2021), which makes a comparison between language switching and task switching very difficult. Also, methodological differences within one paradigm (i.e., language switching or task switching) might be larger within than across the paradigms. Taken together, searching for differences between language switching and task switching (or between language multitasking and multitasking in general) is probably the wrong question. At least, it might be a question that will never be answered in general – mainly because the question itself is too general (as for the question about differences between women and men, on a very general level, we can certainly state that there are differences between language switching and task switching). Thus, we probably need to ask more specific questions, for instance, about which characteristics of language control are shared with more general cognitive control. In language processing, different processing stages have been studied very well (i.e., semantics, lexical selection, phonology, etc.) so that research on language switching might provide us a much more precise insight into which stages are affected by control (beyond stimulus encoding, response selection, and response execution). Along these lines, future questions might be in which way research in one domain might benefit from the other domain. In the specific case of language multitasking, one could ask what research in multitasking could learn from language multitasking research. In this final section, we intend to provide topics and ideas for which research on multitasking might learn from research on language multitasking.

Starting with a methodological aspect, we suggest that the research in the domain of cognitive control/multitasking could benefit from measures developed in the language-switching literature that have not yet been investigated beyond the bilingual domain. One example here could be the blocked language order effect (e.g., Van Assche et al. 2013; Wodniecka et al. 2020). The blocked language order effect can be measured with pure language blocks and indicates the worse performance in a pure language block following a pure language block in the other language as compared to performing the pure language block without a previous block. The blocked language order effect is assumed to be another measure of transient, proactive language control (Declerck 2020). A further measure is the reversed language dominance effect (see Christoffels et al. 2016), which could also be transferred to task switching studies as a (reversed?) task dominance effect. Thus, research in the area of language switching provides several measures that could be interesting to examine proactive control in other research areas.

Next to this methodological aspect, we would like to point out that language has a very special role in our lives. Every day, we speak and listen and we read and write. Even people who cannot use one of their sensory or response modalities can communicate using language (e.g., through sign language and braille). Language is such a powerful tool in our life that it is hard to imagine "tasks" which have the same relevance for our life – and which could be used in task-switching studies. Thus, one could even argue that language switching already allows us insight into a more ecologically switching behavior.

Yet, it is also obvious that the language-switching paradigm cannot represent a completely natural situation in which language multitasking tasks place. In most language-switching studies, single words have to be produced or perceived, while natural communication involves phrases and sentences, thus including a more complex material. Importantly, in sentence production and perception, not only the meaning of words (i.e., their semantic) is relevant but also the rules that guide the combination of words (i.e., syntax). There are language-switching studies that used more complex stimulus material. For example, Contreras-Saavedra and colleagues (Contreras-Saavedra et al. 2021b) used words that also include morphosyntactic information. More specifically, next to the language itself, also the composition rule of either two-digit numbers (is the decade named before or after the unit) or compound words (is head-morpheme before or after the modifier-morpheme) was repeated or switched. The results for both language-production tasks (naming) and language-perception tasks (number comprehension or distance calculation) showed that a language-repetition benefit (i.e., a language switch costs) was only present when also the composition rule was repeated. Thus, these studies clearly show an influence of syntactic information in language switching.

Other studies also included syntactic information by using phrases or sentences in language-production tasks like reading aloud mixed language text (e.g., Gollan and Goldrick 2016, 2018) or phrase production when describing action pictures (Tarlowski et al. 2013). Similarly, syntactic information was also implemented in language switching using language-perception tasks like sentence reading (e.g., Bultena et al. 2015; Gullifer et al. 2013; Philipp and Huestegge 2015). In general, language-switch costs were also observed when more complex material was used. However, there seems to be a reduction of switch costs the more syntactical information is guiding the language switching (e.g., Declerck and Philipp 2015b; Gollan and Goldrick 2018).

This influence of syntactical information might also provide new ideas for research in the field of task switching or multitasking, that is, complex actions like changing the gear when driving have certain goals (which is comparable to the intention to communicate a specific information). As in communication, complex actions are constructed of specific subtask with individual "meanings" (comparable to the semantics of words in language processes). These subtasks have to be performed in a certain sequence as, for example, changing the gear only works when we step on the clutch at the correct time (this sequence is comparable to the syntax in language processing). Thus, when switching between tasks that require more complex actions than simple key presses, the "syntax" (i.e., the order of subtasks) might also play a role and influence cognitive control. There is already evidence that the order of two relatively independent subtasks in dual-task research plays a role (e.g., Hirsch et al. 2017; Huestegge et al. 2021; Luria and Meiran 2003; Strobach et al. 2021). Yet, the idea could be even extended to more complex actions with a larger number of subtasks, in which the subtasks actually form a larger task. In such cases, switching between two tasks might be affected by the overlap in task structure, with smaller switch costs when a similar structure in both tasks is present (cf. the overlap in syntax in the study of Declerck and Philipp 2015b).

A further difference between task and language switching becomes apparent, when we have a look at the role of concepts in language switching. When people switch between languages in a language-production task, they may switch the language, for example, from German to English, but the concept, the meaning of what is expressed, remains the same. Similarly, in a code-switching situation, a speaker might alternate between languages but the meaning that he/she wants to express stays the same. In language-switching with language-production tasks, this is comparable, as translation-equivalent words in different languages are "equivalent" in their meaning (of course there are sometimes subtle difference between languages, especially with more abstract words; see, for example, the English word education for which two distinct words are used in German: Bildung and Erziehung). When we consider tasks in a task-switching study, switching the task typically also means a switch in the stimulus and/or response meaning, that is, switching from a magnitude to a parity decision, although the stimuli stay the same, means that the digit "4" is not meant to indicate a smaller number than 5 but an even number. One option to keep the meaning of stimuli (in perception tasks) or responses (in production tasks) the same is modality switching. For instance, when participants switch between responding with a right vs. left key press or saying right vs. left in a magnitude task, the meaning of the response is comparable across response modalities. Nevertheless, it appears difficult to consider a "dense task switching context" in which people switch between response modalities in the course of task processing. Yet, maybe the distinction between a "dual-task context" and a "dense task switching context" or the consideration of "task 2 learners" and "balanced multitaskers" could bring new ideas in the research of multitasking.

Finally, as we have already pointed out before, one aspect in which language switching and task switching certainly differ is the focus on language proficiency in language-switching studies. Put differently, in language switching, the language proficiency in the used languages and the frequency with which participants switch between languages in daily life lead to a characterization of both participants (e.g., L2 learner vs. balanced bilinguals) and of contexts (i.e., dual-language context vs. dense-code switching context). In task switching, in contrast, the proficiency of participants in the tasks and the frequency of switching between exactly these tasks are typically not considered.

Considering the distinction of contexts, we would like to refer to one very specific aspect from research on code switching that might be interesting for research on multitasking. More specifically, in real-life code switching, one question of interest deals with transition points at which speakers tend to switch from one language to the other. There was a lot of empirical evidence that switching from one language into the other does not occur randomly in code switching situations (for a review see Van Hell et al. 2015). Among other factors, it was argued that code switching occurs when both languages can remain activated in parallel and language control allows lexical selection from both languages ("open control," cf. Green and Wei 2014; Green 2018). Transferring this to the area of multitasking, it might be interesting to test situations in which two continuous tasks can remain activated in parallel and participants are free to process them as they want. According to the idea that different bilingual contexts require different forms of language control (Green and Abutalebi 2013), also less (inhibitory) cognitive control might be relevant in such task-switching or multitasking settings.

5 Conclusion

Language multitasking is a fascinating research field that allows researchers insights into language control mechanisms. Many topics in language multitasking are still under discussion (see, e.g., the heated discussion on the bilingual advantage), but the current state of the art already provides a detailed picture on reactive and proactive language control in language switching. Language control works remarkably well in real-life situations, allowing us to perceive/comprehend and to produce different languages in a flexible manner. Thus, an important step in the research of language switching will be to bridge the gap between experimental research and real-life situations.

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Part III
Neural Basis of Multitasking

The Neural Basis of Simultaneous Multitasking

Kelly G. Garner and Paul E. Dux

As humans, we show striking adaptability in our behavioural repertoires. Across the globe, we build shelters and craft attires that are suited to the local conditions. We develop mathematics and technology that allow us to make new connections across societies. We even rapidly engage in large-scale reorganisation of our social conduct to mitigate the threat of a novel virus. Despite this apparent ability to adapt and assimilate a large variety of behaviours to suit our current contexts, we show some striking limitations in how many tasks we can perform at any given moment. Although some behaviours can appear to be performed concurrently with ease, such as talking while walking, we show a stark inability to combine other tasks and skills; imagine compiling a grocery list while recalling your partner's phone number. The observation that attempting to perform multiple tasks concurrently results in at least one of those tasks being performed more slowly, and with less accuracy, was among the first to be made when cognitive psychology was emerging as a scientific discipline (Telford 1931; Welford 1959). Interestingly, among these early observations, it was also noted that such performance costs can to some extent be reduced with practice (Telford 1931), suggesting malleability in how tasks are performed that carries consequences for multitasking operations. Since then, efforts have been made into understanding the nature of the putative operations that give rise to multitasking costs, the neural computations and architectures that instantiate those operations, and the neural and functional changes that drive improvements in

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Visualisations by K.G. Garner & David Lloyd.

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multitasking performance. The aim of this chapter is to synthesise the in-roads that have been made into understanding the neural basis of multitasking costs and their practice-induced remediation and to use that knowledge to propose the next steps forward in our understanding.

1 Approaches to Understanding the Neural Basis of Multitasking

Approaches to understanding the neural basis of multitasking have largely followed three theoretical traditions. Here, we provide a taxonomy of the theories and empirical insights that have been garnered from these three approaches (see Fig. 1). On one hand, researchers have used models of the cognitive architectures that are designed to explain multitasking costs in order to make predictions of what should be observed at the neural level (see Marois and Ivanoff 2005). In this approach, which we shall refer to as the *cognitive architectures* approach, the start point is a model that provides a descriptive account or a computational representation of the operations that could underpin multitasking performance. Given the set of procedures or operations posed by a model, researchers then seek to make predictions regarding the neural correlates that should be observed when humans perform tasks designed to capture the cognitive phenomena of interest, in the current case *multitasking*. As a relevant example, the act of making the correct response given a sensory input, such as waving hello upon seeing a friend approaching, is assumed by multiple models to be composed of several distinct processing stages (e.g. Brown and Heathcote 2008; Ratcliff and McKoon 2008; Sternberg 1969) such as identification (it is your friend's face), response selection (a wave is better than a frown), and response execution (your hand moves from side to side). If something happened so that completing a stage is more difficult (your friend is being responsible and wearing a COVID mask), then the duration of the relevant stage should be increased. Researchers can translate such anticipated duration changes to what should be observed in recorded brain activity. In this example, neurons that care about response selection should be active for longer; therefore signals that correspond to neural energy usage, such as the blood oxygen level-dependant (BOLD) signal detected by functional magnetic resonance imaging (MRI), should be stronger when choosing between a wave and a frown when either is more difficult. In the discussion below, we show how such models have generated the hunt for neural correlates in the context of multitasking performance and how a frontoparietal network has been implicated as important, regardless of the specific motivating model.

A second approach offers an alternate inferential route, going from observations of systems-level neurophysiological phenomena to hypotheses regarding plausible operations that underpin multitasking performance, given the observed neural behaviour of the system. We refer to this as the *systems architecture* approach. Rather than taking a specific model for multitasking performance, this approach

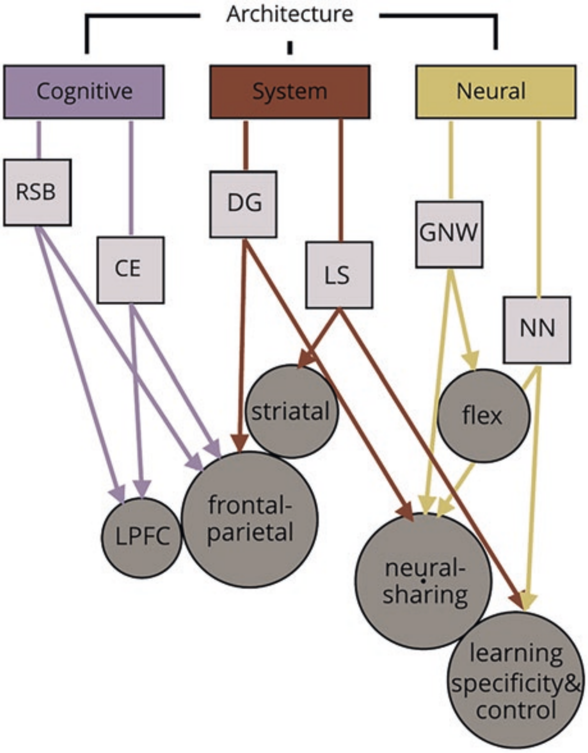

Fig. 1 A taxonomy of the approaches toward understanding the neural basis of multitasking. Three broad approaches are identified by the taxonomy: *cognitive architectures, system architectures, and neural architectures*. Specific theoretical positions (squares) within each approach have yielded convergent and unique conclusions (circles) regarding the neural basis of multitasking. Response-selection bottleneck (*RSB*) and central executive (*CE*) models have implicated a set of frontal-parietal regions and in particular the lateral prefrontal cortex (*LPFC*) as underpinning multitasking performance. Observations of task performance across multiple domains (*MD*) have similarly implicated the importance of frontal parietal regions and have motivated the theory that associative neurons coding relevant information across tasks must be shared between tasks during multitasking, giving rise to costs. Studies of the brain's learning systems (*LS*) have extended the hypothesis space by suggesting that striatal-cortical connections are part of the neurophysiological infrastructure that gives rise to multitasking costs. Moreover, findings garnered from this approach suggest that multitasking costs may stem from an initial over-recruitment of shared neurons, possibly owing to error in encoding, or insufficient experience to differentiate the task space. A spiking neural network model of a global neuronal workspace (*GNW*) shows that a system containing neurons that are recruited to route task-relevant information across tasks can give rise to flexible behaviour (*flex*) but requires a serial processing strategy, thereby causing multitasking costs. Neural network (*NN*) models (defined in text) show that systems consisting of units that contribute to multiple task representations (and are thus shared between tasks) are better able to generalise previous learning to novel tasks, at the expense of multitasking capability

instead asks which observations of neural activity could be relevant to the formation of a hypothesis regarding multitasking operations, given the key behavioural signatures of multitasking performance. For an example of this approach, and as will be discussed in more depth below, the observation that multitasking costs are pervasive across most mental tasks has motivated investigations into which brain systems show sensitivity to task-relevant information that is convergent across multiple domains such as attention, memory, and response selection (Duncan 2010, 2013). Similarly, the observation that multitasking costs reduce with practice suggests that a study of the brain's learning architectures may garner clues for how experience-dependant changes in task representations may give rise to attenuated multitasking costs (Dux et al. 2009; Garner et al. 2014, 2020; Garner and Dux 2015). This approach has implicated sensitivity of a common set of frontal, parietal, and striatal regions to information pertinent to the current task goals, such as the identity or the colour of the green 'A' on the screen, dependent on which aspect of the letter you are currently reporting. The question that follows is: What kind of functional properties could these region's constituent neurons carry that would give rise to this observed phenomena *and* also give rise to multitasking costs and their practice-related attenuation? We show how the concept of neurons that adapt their responses to encode the current cognitive episode can provide explanations as to why the human brain shows great flexibility in the behaviours that are performed, at the expense of multitasking capability. Specifically, neurons that respond to multiple tasks need to be shared between tasks, and the extent of this sharing may give rise to multitasking costs.

The third approach, which we call the *neural architecture* approach, derives models inspired by what we know about how neurons function and relates their computational properties to how individuals undertake multiple tasks concurrently. In this approach, researchers leverage models that characterise neural function in order to build networks that perform tasks analogous to the cognitive phenomena of interest. For example, functions describing how the membrane potential of a neuron changes in response to synaptic inputs and injected currents (see Dayan and Abbott 2001) can serve as computational units within a network. By constructing a simulated task environment within which the network can perform, researchers can determine which assumptions about connectivity rules produce responses that are comparable to observed behavioural or neurophysiological data. Such assumptions include whether a given unit is excitatory or inhibitory, from where units receive inputs or project outputs, and what causes the coupling strength between units to increase or decrease. By making these assumptions explicit, we can make inferences regarding how a system can be wired to effectively produce behaviour, what kinds of computations the system must perform to produce the observed outputs, and which advantages and disadvantages this confers for new tasks or operations. We show below how these approaches have yielded further insight into the advantages of systems that share units between constituent tasks. Neural sharing may drive behavioural flexibility and facilitate learning of novel tasks, at the direct expense of multitasking ability.

Throughout our taxonomy of investigations into the neural basis of multitasking, we seek to consider the ensuing insights in light of what we believe to be key criteria for understanding how neural function gives rise to multitasking costs. According to computational biologist David Marr (1982), understanding of the central nervous system occurs at three levels: First, we can understand the nature of the problem that is expressed – as in, what is the problem that the brain is solving? Here, an initial answer to this question could be 'the problem of performing multiple tasks concurrently and accurately'. However, we will argue that what is revealed from our taxonomy is that this question is surprisingly difficult to answer definitively, and yet how one answers the question has significant implications for how we derive the subsequent stages of understanding. The second level advanced by Marr concerns the algorithmic or representational level, i.e. how does the system do what it does? How does the system concurrently represent multiple stimuli and goals, and what procedural manipulations are acted upon those representations to produce multiple responses that are timely and accurate? We show how empirical investigations into the neural basis of multitasking have largely sought to understand which putative algorithms are most likely, given assumed mappings between certain procedural features and observable neural correlates. The third level of understanding concerns the physical implementation of such operations, i.e. how could the brain's neural architecture instantiate the representation and performance of multiple tasks? We discuss some initial insights into this level of understanding the neural basis of multitasking and suggest avenues for further investigation.

2 Observing the Multitasking Brain

Although we shall argue throughout this chapter that it is a challenge to pin down exactly what problem the brain is solving when we observe incurred multitasking costs (i.e., the 'why' of multitasking costs), we can certainly characterise what we do observe when participants multitask in the lab. Multitasking has been investigated with an array of paradigms that have combined everything from unspeeded perceptual judgements (Raymond et al. 1992) to continuous complex tasks such as prose comprehension (Cho et al. 2015) and driving (Levy and Pashler 2008). Here we largely focus on paradigms requiring the speeded completion of two temporally overlapping sensorimotor tasks, as this is where the majority of efforts to understand the cognitive architectures underpinning multitasking have been focused (Logan and Gordon 2001; Meyer and Kieras 1997a, b; Navon and Miller 2002; Pashler 1994; Salvucci and Taatgen 2008; Tombu and Jolicœur 2003). Constituent tasks in these paradigms typically involve mapping two or more stimuli, such as letters or sounds, to the appropriate motoric output, such as a key press or a vocal response.

In many multitasking paradigms, task 2 is presented subsequent to task 1 at increasing intervals, typically ranging from 100 to 1000 ms, in order to vary the demands placed on the system (see Pashler 1994 for a review). Under these conditions, it has been consistently observed that the duration of task 2 performance increases as the intervals between the two tasks decrease. Slowing to task 1 performance has also been observed, more variably, but particularly when the two tasks are presented simultaneously (Maquestiaux et al. 2008; Welford 1959). Importantly, multitasking costs are evident even when tasks do not overlap in the modality of stimulus inputs and response outputs (Hazeltine et al. 2006; Hazeltine and Ruthruff 2006; Pashler 1990). For example, one task can entail making a manual response to a visual input, while the second requires a vocal response to an auditory output – even under such conditions substantial multitasking costs are found. This suggests that the locus of multitasking limitations lay outside the (initial) parsing of sensory inputs (Johnston and McCann 2006) or the execution of a motor response (Klapp et al. 2019). However, the mapping between modalities can influence multitasking performance, for example, costs are lower when pairing visual-manual with auditory-vocal tasks relative to when pairing auditory-manual and visual-vocal tasks (Hazeltine et al. 2006). The reason as to why certain modality pairings confer performance benefits remain to be fully elucidated but may relate to the frequency with which modalities are naturally paired. For example, we gain experience producing vocalisations in response to auditory inputs with each conversation we conduct.

Observations that task 1 performance was largely spared from multitasking costs (Pashler 1984) motivated ‘bottleneck’ theories which proposed that task 2 slowing was caused by processing limitations of a single channel at the locus of task 1 response selection, i.e. while task 1 processing proceeded unimpinged, task 2 response selection had to await for availability of the serial processing mechanism (Pashler 1994). Moreover, the finding that practice on task 1 alone is sufficient to reduce or even overcome multitasking costs (Ruthruff et al. 2003, 2006a, b) suggests that reducing the amount of time required for the execution of task 1 operations causes reduced impingement on task 2 operations, which is in accordance with the assumptions of the bottleneck model. However, the single-channel serial bottleneck model is an unlikely candidate to account for the consistent observations that task 1 performance is affected in many multitasking contexts (see Strobach et al. 2015, for a review), that the response selected for task 1 can be influenced by the response required for task 2 (Bratzke and Janczyk 2020; Janczyk et al. 2018; Ko and Miller 2014; Miller and Alderton 2006), and that sensory evidence can be accumulated toward the task 2 decision during performance of task 1 (Zylberberg et al. 2010). If multitasking costs are to be thought of as stemming from limitations in a mechanism that supports response selection, as has occurred in some investigations into the neural correlates of multitasking, then the data largely favour modified accounts of the bottleneck model that postulate that multitasking costs are due to limitations of a mechanism that supports response selection and allocates this capacity between the two tasks (Tombu and Jolicœur 2003). It is also worth noting that the conclusion that the limitations which give rise to multitasking costs are located at a central response-selection stage is by no means conclusive. For example, theory and data have supported the idea that the bottleneck that gives rise to multitasking costs may be motoric in nature (Bratzke et al. 2009) and that a bottleneck exists at the point of timing the initiation of a pre-programmed response (Klapp et al. 2019), which is something that can presumably only occur once a response has been selected. However, we have largely focused on 'central bottleneck' accounts here, as this account has driven a substantial portion of the cognitive architecture efforts to understand the neural basis of multitasking.

The above mentioned bottleneck theories postulate that multitasking costs are observed because of delays incurred to the performance of the task itself. It is also possible that multitasking costs arise due to functions the brain must perform as a consequence of being required to manage multiple tasks. To wit, the whole of multitasking is greater than the sum of the constituent tasks. For example, an executive system may be required to programme and schedule task performances when multiple tasks are present (Logan and Gordon 2001; Meyer & Kieras, 1997a, b; Salvucci and Taatgen 2008). Investigators have sought to identify such extra sources of slowing that may contribute to multitasking costs. For example, completing single tasks in a mixed block of trials, where the participant does not know ahead of each trial which of the two single tasks will be presented, results in longer response times (RTs) relative to when a block only contains one single task type (Pashler et al. 2000). This suggests that establishing the task set, i.e. the implemented rules for mapping a given sensory input to the task goal, may be one source of slowing that causes performance costs under multitasking conditions. Moreover, the observation that practice on constituent tasks that are presented together as a multitask results in larger reductions in costs than when both the tasks are practiced as single tasks (Strobach 2019) suggests that something beyond the execution of each task can be trained to influence performance. Such findings have been interpreted as support for theories postulating that a central executive system is recruited to manage the execution of multiple tasks.

Collectively, these empirical features have helped inform the models derived to explain how multitasking costs arise and have therefore shaped the landscape of insights yielded by the first body of work in our taxonomy, i.e. the investigations seeking to determine whether neural responses exhibit features that would be expected given the existence of a response-selection bottleneck or a central executive that gives rise to multitasking limitations.

3 Cognitive Architectures: Hunting the Putative Neural Correlates of a Response-Selection Bottleneck or a Central Executive

In order to seek evidence for which cognitive architectures could likely give rise to multitasking costs in the human brain, researchers have sought to extrapolate how a proposed cognitive mechanism could manifest in neural correlates. Empirical investigations have then been constructed to determine whether or not the evidence suggests the presence of such a correlate. This is an immensely difficult task given that these models are not couched in the functions of neurons and that the neuroscientific tools available to researchers when undertaking such work with human subjects result in observations of neurobiological function that are indirect. For example, functional magnetic resonance imaging (MRI), which has often been applied in this context (Marois and Ivanoff 2005), measures the movement of oxygen concentration in the blood (BOLD signal), which serves as a proxy for the energy usage incurred by increased neural activity (Logothetis 2008). Moreover, the spatial resolution of MRI is quite large (~1–3 mm^3), with each voxel consisting of hundreds of thousands of neurons[1]; therefore each voxel likely contains a mixture of underlying neural responses on any given observation. As such, any interpretations of such studies must include the caveat that we currently do not have a forward model that can map for us exactly what we should see in the observed neural signal, given the proposed cognitive operations, and that multiple other explanations for the observed neural correlates likely remain viable.

3.1 Response-Selection Bottlenecks

Bottleneck models of multitasking limitations inherit their structure from the concept that the performance of a task can be parsed into processing stages (Sternberg 1969). In this case, sensorimotor performance is assumed to be composed of three distinct stages: perceptual and response execution stages that encompass the analysis of incoming sensory inputs and the process of physically performing the movement required by the manual response and a central stage that maps the input to the appropriate output. Of import, it is this central stage that is hypothesised to be limited in processing capacity. According to theoretical accounts which posit that the locus of multitasking costs lay at the central stage of sensorimotor processing (Pashler 1994; Welford 1952, 1967), performance slowing occurs when the interval between two tasks is short, as task 2 central stages must wait for sufficient availability of the underlying mechanism. Consequently, these stages may not proceed until task 1 central stages are complete. The strength of this theory lay in its simplicity and the quantitative predictions for behaviour that have largely been corroborated (Pashler 1994; Tombu and Jolicœur 2003), although there have been many observations of phenomena not captured by these models (Huestegge and Koch 2010; Ko and Miller 2014; Miller and Alderton 2006; Navon and Miller 2002; Ulrich and Miller 2008; Zylberberg et al. 2010). Nevertheless, predictions made by these models regarding the duration of central processing stages have motivated searches for the neural correlates of this response-selection bottleneck. For example, a key prediction made by these models is that task 1 difficulty manipulations

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[1] https://cfn.upenn.edu/aguirre/wiki/public:neurons_in_a_voxel

should delay the start and end times for which task 2 response selection occurs. This has motivated the hypothesis that any brain regions supporting such a mechanism should show activity (i.e., changes to the BOLD response) that scales with task 1 difficulty manipulations. Importantly, any such brain region should also show sensitivity when each single task is performed in isolation, given that the proposed central stage of processing is assumed to underpin performance of each sensorimotor task. A series of studies have indeed demonstrated BOLD activity changes that fit such a profile and that this pattern is typically and consistently observed in the left LPFC. For example, Marois et al. (2006) manipulated the number of choice alternatives for tasks administered under both single-task and dual-task conditions and observed increased peak BOLD amplitude in the dorsal pre-motor and lateral prefrontal cortices. These regions were also insensitive to a perceptual difficulty manipulation that increased task 2 performance time without influencing response-selection demands; one interpretation of this finding is that these regions specifically reflect the response-selection limitations that are assumed by the central bottleneck model.

One issue with using fMRI to interrogate the neural correlates of response-selection limitations (or, cognition in general) is that the temporal resolution of the signal is poor. A typical scan of the human brain takes around 1.5–2 seconds, which is longer than that required to perform the sensorimotor tasks employed in multitasking paradigms. However, it is possible to adjust experimental manipulations and/or analysis techniques in order to match response-selection demands to the temporal resolution of MRI. For example, Dux et al. (2006) sampled brain activity while participants completed single and multitask conditions with sufficiently taxing response demands to bring RTs within the temporal resolution of fMRI. This approach carries the assumption that there is a quantitative, rather than qualitative, change in how the task is performed under easy conditions relative to hard ones. The authors then leveraged the central bottleneck model to derive predictions about the shape of the hemodynamic response function (HRF) that should be observed in brain areas that underpinned such a bottleneck. The HRF characterises the rise and fall of the BOLD signal in response to experimental perturbations. The prediction was that the duration of the HRF should be extended in multitask conditions relative to single-task ones, given that a brain region underpinning response-selection limitations would contribute computations for a longer period in the multitask condition. Activity in LPFC showed a protracted response signature that corresponded to the increased response-selection demands, corroborating Marois et al. (2006) to show that activity in this region matches the anticipated signature of a central response-selection limitation that gives rise to multitasking limits. Moreover, this group of researchers showed that this protraction of LPFC activity was reduced after participants practiced the multitask over multiple sessions (and therefore reduced multitasking costs) (Dux et al. 2009), which is in line with the prediction that practice reduces the duration of response selection for task 1. However, this practice study did not contain a control group,

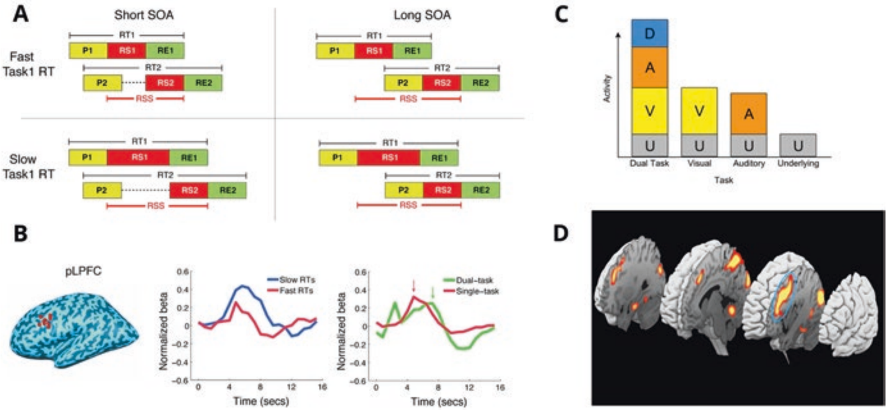

Fig. 2 Showing the logic and most consistent findings from investigations seeking to map either the response-selection bottleneck or the central executive to observable neural correlates. Panel (**a**) The central bottleneck model with perceptual (P), response selection (RS), and response execution (RE) stages of sensorimotor processing (Pashler 1994). According to the model, the duration of engagement of central and limited response-selection stage (RSS) is extended for slow response times and for dual relative to single-task conditions. If a brain region contains neurons performing such a response-selection function, it is assumed that the haemodynamic response function (HRF) will show a protracted response for slow relative to fast RTs and for dual relative to single task trials. (**b**) Such a response has been most consistently observed in the posterior left lateral prefrontal cortex (pLPFC). (**c**) The logic of investigations seeking to map neural correlates to a 'central executive'. As something extra is recruited to manage the performance of multiple tasks, brain regions containing neurons underpinning such an operation should show a response in this condition that is greater than the sum of the visual (V) and auditory (A) single tasks that make up the multitasking operation. (**d**) This approach has yielded a response pattern that consistently includes the pLPFC (circled in blue). Panels A and B are taken from Dux et al. (2006), panel C is reproduced from Szameitat et al. (2011), and D is reproduced from Schubert and Szameitat (2003)

so it is hard to disentangle whether it was a practice-induced attenuation of multitasking or some other factor such as reduced task novelty, or motivational factors, that drove the result.

The above studies illustrate that it is possible to find a putative neural correlate of central capacity limits in the human LPFC. As will be seen in the next section, this brain region consistently shows activity patterns that can be inferred as corresponding to the increased cognitive demands induced by attempting multitasking. This is comforting in the respect that it appears that this region consistently shows sensitivity to multitasking demands. In the current context, the observed patterns of activity have been taken as showing the viability of models that propose a central limitation that struggles to support multiple response-selection demands. In the next section, we shall see how a comparable approach seeking to find correlates of a central executive that schedules the execution of multiple tasks also elicits findings that converge on the LPFC as a region of importance (see Fig. 2).

3.2 Seeking the Central Executive

Just as the response-selection bottleneck model has been used to derive hypotheses about what one could expect to observe in fMRI signals, so too has the concept of a 'central executive' motivated a comparable body of work. Importantly, theories that postulate that multitasking costs are due to an overarching executive process that monitors and manages task schedules do not assume that there is a capacity limitation in the function of mapping a stimulus input to a response output. Multitasking costs have instead been attributed to stemming from the following: an adaptive task scheduling mechanism that acts to reduce overload of peripheral processors (Meyer and Kieras 1997a, b), a serial processor that coordinates subtasks to reduce resource conflict (Salvucci and Taatgen 2008), and an executive module that adjusts the parameters for evidence accumulation, given the current task set (Logan and Gordon 2001). Across all these models, there is the notion that multitasking involves a set of cognitive functions that are greater than the sum of the constituent task parts, i.e. something extra is required in the multitasking context that is not required in the single task context. Thus, the approach typically taken in studies looking for a putative neural correlate is to find brain regions that show greater BOLD activity than is observed by the summed activity elicited by component tasks. Moreover, and in contrast to the central bottleneck model, such brain regions need not necessarily overlap with brain regions that are recruited to perform single sensorimotor tasks.

Investigations utilising such a method have uncovered neural correlates spanning the LPFC (Collette et al. 2005; Schubert and Szameitat 2003; Szameitat et al. 2002, 2006), middle frontal gyrus (Szameitat et al. 2002), anterior cingulate cortex (Dreher and Grafman 2003), parietal cortex (Collette et al. 2005; Schubert and Szameitat 2003; Szameitat et al. 2002), and subcortical regions (Collette et al. 2005). However, once task-preparation processes have been controlled for, regions showing greater activation in dual-task relative to single-task conditions broadly overlap with the regions elicited by the single tasks alone (Erickson et al. 2005). In a potential challenge to the predictions made by central executive models, at least two investigations have failed to find brain regions that show increased activity specific to the dual-task condition (Dux et al. 2006; Jiang et al. 2004). However, given the poor temporal resolution of fMRI, it is challenging to rule out whether this increased activity was too short to detect. Using a measure of how much BOLD activity in 'sensory processing regions' (e.g. the fusiform face area) can be explained by activity in the LPFC under varying task contexts (i.e., single vs dual-tasks), Stelzel et al. (2006) showed that activity in task 1 relevant sensory regions was better explained by LPFC activity in the presence of the task 2 stimulus, regardless of whether or not the participant was required to perform task 2. This has been interpreted as evidence that a protective mechanism is invoked to protect task 1 that is separate to task 2 performance, as could be expected from a central executive. Furthermore, parametric manipulations of other task conditions that should influence the function of a central executive, such as the predictability of task order, have consistently been associated with increased BOLD activity in the LPFC (Stelzel et al. 2008; Szameitat et al. 2002, 2006).

It is interesting that regardless of the theoretical motivation, BOLD activity in the LPFC has covaried with experimental manipulations of multitasking demands. However, it is difficult to discern exactly what these BOLD activity changes reflect in terms of putative algorithms, given the lack of specificity in the forward mapping from proposed cognitive operations to observed neural responses. What these results do show is that any effort to determine how the neurophysiological hardware could support the putative mechanisms of multitasking should take into account the nature of inputs, outputs, and local LPFC processes and perhaps leverage this information to narrow down exactly how a biologically plausible model would act to give rise to multitasking costs. Furthermore, some clues to the cause of this convergence may potentially be found in the rodent and monkey dual-tasking literature, where neurophysiological recordings suggest that there is indeed a network that fits the proposed profile of a central executive and that it is intertwined with the circuits that support single-task processing in the prefrontal cortex (Lebedev et al. 2004; Messinger et al. 2009; Olton et al. 1988; Pang et al. 2001).

At this point, we understand that performance suffers when we seek to undertake two tasks. The models and/or algorithms that have been proposed to account for these phenomena include a serial or capacity limited channel underpinning the translation of stimulus inputs to response outputs and/or an executive mechanism that titrates task parameters or schedules the performance of subtasks in accordance with available resources. In all cases, the search for proposed neural correlates has largely converged on predicted patterns of BOLD activity being most prominently observed in LPFC. It is interesting to consider how these strands of inquiry inform the ‘why’ of multitasking, specifically, what problem is the brain solving when we observe multitasking costs? Bottleneck models focus solely on the successful performance of two sensorimotor tasks. It is indeed true that we are often required to perform multiple tasks, but a deeper consideration of the ‘why’ question does suggest that bottleneck models (in this case) largely serve to predict the empirical phenomena of multitasking costs rather than demonstrating why a system would organise in a manner that induces a single or limited capacity channel for response selection. On the other hand, models proposing a central executive do probe further into the ‘why’ question; these models suggest that the performance of multiple tasks requires resource management and that multitasking management often (and optimally) involves delaying access to resources for certain subtasks. Largely though, these models assume that the problem the brain is seeking to solve is the performance of multiple tasks, i.e. the brain is trying to solve multitasking. Later in this chapter, we will see that models that seek to emulate the function of neurons in systems that can perform sensorimotor tasks have yielded some rather different answers to this question.

4 System Architectures: Using Neurophysiological Observations from Broader Domains to Shed Insight into the Neural Basis of Multitasking

Of course, our understanding of the neural basis of multitasking need not only be informed by experimental manipulations of human multitasking scenarios and the models that seek to explain the observed phenomena. Interesting insights have been leveraged from the broader literature on domain general human cognition (Duncan 2010, 2013) and animal models of sensorimotor action (Watanabe and Funahashi 2018). In the case of the former, by observing the patterns of BOLD responses across a range of complex cognitive domains such as working memory, response conflict, and challenging sensorimotor processing, Duncan (2010, 2013) demonstrated that a common set of overlapping frontal and parietal brain regions showed activity covarying with the difficulty of the task, regardless of the specific domain of the paradigm. The inference that followed was that frontal and parietal brain regions constitute a multiple demand network, whose constituent neurons flexibly reconfigure their response properties to be tuned for the current cognitive episode. Duncan (2013) proposed that just as artificial intelligence models can solve complex tasks by breaking them down into more readily solvable subgoals (Sacerdoti 1974), so too does the brain, and that the contents of the current mental episode or subgoal are encoded into the frontal-parietal multiple demand system.

Empirical efforts to determine whether frontal and parietal neurons do exhibit such properties have typically leveraged information-based approaches to the analysis of neural data, to determine which task rule is currently active in a given experimental context (Jackson et al. 2017; Jackson and Woolgar 2018; Marti et al. 2015; Tamber-Rosenau et al. 2013; Woolgar et al. 2011, 2016). The research reviewed in this chapter up to this point have largely used activation-based approaches, where the goal is to determine the extent to which the amplitude of the BOLD response systematically changes as a function of manipulations of interest. Given that there are hundreds of thousands of voxels in one brain scan, it is very easy to identify statistically significant voxels by chance. Therefore, under this approach, it is important to identify clusters of voxels that show a comparable association between response amplitude and the experimental manipulations (Nichols 2012). Thus, neighbouring voxels are pooled to answer the questions: ‘Does this set of voxels (area x) show systematic activity changes that correspond to my experimental manipulation?’ ‘At a cluster level, do I have more significant clusters than I could expect by chance?’ This approach works well to identify whether or not a brain region is responsive to an experimental condition but provides little information for how well that activation maps to the cognitive operations that may underpin performance in a given experimental condition. For example, although activation may reliably increase between single and multitasking conditions, it does not necessarily follow that the activation change corresponds to a neural code that contributes to multitasking performance. It could, for example, reflect an increasing quantity of stimulus energy on multitask trials.

In contrast, information-based approaches ask the following: ‘Given this set of voxels (i.e., the voxels in area x), can I find patterns distributed across the voxels that reliably map to my experimental conditions?’ In effect, this means that a classification algorithm, such as a support vector machine, is trained on a set of voxels to map a function between feature space (i.e., activation level of each voxel) and the experiment space (e.g., experimental conditions, such as specific stimulus-response mappings, or the current task rule). This classification approach can detect differences between conditions, given a true bias exists in the mapping of neural response to the dimensions of measurement. For example, such classification of fMRI data assumes a true spatial bias in the voxels that increase their activity given one condition, relative to another (Haxby 2012; Serences and Saproo 2012). Once trained, the algorithm is then tested on new, as yet unseen, data. If classification performance is above chance, then the set of voxels (or timepoints or whichever features of the data that are under interrogation) are said to contain information about the experimental conditions. Well-controlled experiments can ensure that the only possible difference between conditions is the phenomena of interest – for example, stimuli and responses can be held constant, but the rule that maps them to each other can vary across conditions, increasing the chance that the classification analysis has detected a code in the neural data that pertains to the mapping of stimuli to responses. Given that information-based approaches seek to identify distributed patterns in the data, this approach is also particularly useful when there is reason to believe that the aggregate average BOLD response within a region of interest may increase for, but not differ between, two conditions, for example, when the same frontal or parietal brain regions show increased activity in the context of two comparable challenging task rules.

Applications of this information-based approach have indeed shown that neural activity recorded from the frontal-parietal cortex carries information about which rule maps a stimulus to a response, even when the stimuli and responses themselves are held constant across all conditions (Woolgar et al. 2011, 2016). Moreover, frontal and parietal neural responses in human and non-human primates show activity patterns that adapt to reflect the current task rule, under experimental conditions where the rules change over the course of a single trial (Jackson et al. 2017; Meyers et al. 2008; Stokes et al. 2013; Watanabe and Funahashi 2014, 2018). Interestingly, and in support of what would be expected by limited capacity models, such decoding methods applied over neural data with higher temporal resolution than fMRI (e.g., magnetoencephalography [MEG]) have shown that frontal and parietal responses show seriality (i.e., one task rule can be decoded at a time), whereas visual and motor cortex responses do not (Marti et al. 2015). Moreover, and in support of the human fMRI work presented above, it has been shown that the activity of LPFC neurons, recorded in awake macaques that have been trained to perform a multitasking paradigm, shows a decreased ability to represent task information when the concurrent task demands increase and that this decrease is proportional to the observed behavioural multitasking costs (Watanabe and Funahashi 2014). Given that the same frontal and parietal neurons are assumed to reconfigure their response profiles to encode the current task demands, the interpretation is that multitasking costs may stem from at least two sources: First, each task will comprise multiple subgoals, some of which will be consecutively represented in order to solve the overall problem of completing the multitask. Second, given the same neurons may be recruited to represent each task, the constituent tasks may compete for representation within the multiple demand system, i.e. neurons that contribute representations to both tasks are overloaded by the current task demands. Note that we will return to the concept of shared representations in the discussion on neural network models below.

Inspired by this account of multitasking limitations, we sought to understand whether practice-induced multitasking improvements could be accounted for by a reduction in shared neural overlap in the multiple-demand system (Garner and Dux 2015). Specifically, we asked the following: If tasks compete for representation in the multiple demand network, can a reduction in this competition account for multitasking improvements? To address this question, we recruited 100 participants, in what we believe to be the largest fMRI study into the neural correlates of multitasking conducted to date. All participants completed a simple multitasking paradigm in the MRI scanner, which consisted of performing two sensorimotor tasks, either as single tasks or together as a multitask. During the subsequent week, half of the participants practiced performing the multitasking paradigm (over thousands of trials), whereas the control group practiced upon a comparably challenging visual-search task. We chose a visual-search task as we did not expect practice of it to lead to multitasking improvements and it allowed us to match extraneous factors such as motivation and reward history between our practice and control groups. Interestingly, we found that not only did frontal and parietal brain regions show practice-induced differences that were specific to the multitasking practice regimen (specifically the pre-supplementary area and the intra-parietal sulcus) but so too did the striatum, or more specifically, the putamen. This is in concert with recent calls that the multiple demand system should be extended to incorporate the human striatum (Camilleri et al. 2018).

To address our specific question, we tested our ability to classify patterns of brain activity in this set of frontal-parietal and striatal brain regions, according to which *single-task* participants were performing, before and after practice. The underlying assumption is that the extent to which the tasks can be classified, using the BOLD response across voxels, should increase as neural overlap in the underlying task representation decreases, i.e. decreased sharing of representations should correspond to an increase in the heterogeneity of the BOLD response across voxels. We then asked whether the extent to which classification improved from pre- to post-practice could predict individual improvements in multitasking practice. We found that this was indeed the case; the greater the increase in classification accuracy from pre- to post-practice, the more multitasking improved (see Fig. 3). Furthermore, this finding was specific to the above-identified brain regions, and no other brain regions,

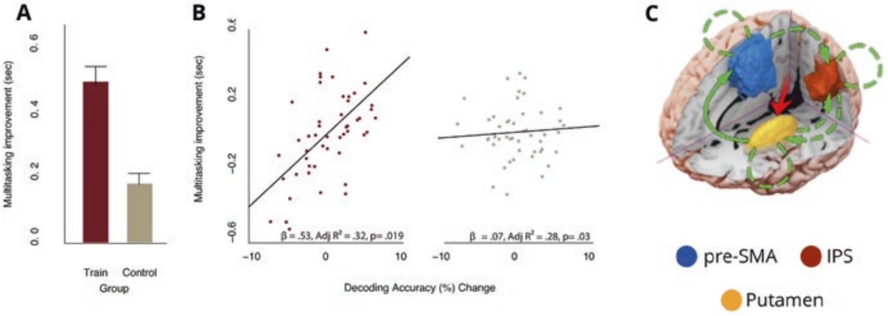

Fig. 3 Practice-related improvements in multitasking occur concomitantly with decreased overlap in task representations, and modulations of the putamen's influence on the pre-SMA. (**a**) In our study of 100 participants (Garner and Dux 2015), multitasking improvement (y-axis) was larger for the practice (train) group than the control group. (**b**) The increase in decoding accuracy from pre- to post-practice (x-axis) in the brain regions of interest (**c**) co-varied with performance improvement to a greater extent in the practice group (left panel, red dots) than the control group (right panel, grey dots). (**c**) The brain regions of interest and the change in network dynamics with practice. Coupling between the putamen and the pre-SMA reduced with practice (Garner et al. 2020)

and to the practice group only. We took this finding as inferring support for the notion that practice improves multitasking by reducing competition for representation within the multiple demand network.

As our findings also implicated that the striatum showed comparable activity changes to frontal and parietal brain regions, we next sought to consider how this neurophysiological structure could possibly interface with the cortex to support multitasking behaviour. Interestingly, striatal-cortical interactions have been implicated in many of the components that make up the process of performing multitasking, but the consideration of their contribution to multitasking performance has been far from extensive (Klapp et al. 2019; Thoma et al. 2008; Yildiz and Beste 2015). For example, multiple theoretical and computational models implicate striatal-cortical circuits as the hardware that implement multiple algorithms via which the brain may implement a single sensorimotor decision, such as the arbitration between potential task-related signals (Gurney et al. 2001), sequential sampling of evidence toward possible outcomes (Caballero et al. 2018), or instantiation of task-set rules (Bornstein and Daw 2011; Joel et al. 2002). Moreover, it has been theorised that the striatum is well placed to send dopaminergic 'teaching signals' to the cortex on the basis of current information, which, owing to the cortex's relatively slower dopamine response dynamics, means that the cortex will only retain task representations that prove to be useful over the longer term (Ashby et al. 2010; Hélie et al. 2015). This is in keeping with theories, developed on the basis of observations in rodents and non-human primates, that the striatum constitutes the neurophysiological architecture that manages the transition between the systems that support novel and practiced behaviours (Graybiel and Grafton 2015; Jahanshahi et al. 2015; Smith and Graybiel 2013; Yin and Knowlton 2006), i.e. between the stages of learning where multitasking becomes more or less difficult. Thus, it appears that the nature of the interface between striatum and cortex changes when tasks are practiced, and this change could mediate the extent of multitasking costs.

We sought to test whether our data could support the notion that the neurophysiology that supports multitasking encompasses the striatal-cortical interface (Garner et al. 2020). To do this, we applied dynamic causal modelling (DCM, Friston et al. 2003) to our fMRI dataset. This technique allows one to propose and compare between plausible networks that may underpin the observed data. Specifically, DCM tests how well activity observed in one brain region can be explained by the activity of one or more other regions. In our case, we sought to understand whether our data, recorded during multitasking and after its practice induced remediation, were best explained by a network where the cortical nodes (pre-SMA, IPS) influenced the activity of the striatum (putamen), or vice versa, or whether connectivity changes were reciprocal between striatum and cortex. Although we observed some differences between hemispheres (see also Filmer et al. 2013, 2017a, b), the data were largely best explained by models that allowed the putamen to exert greater influence on the cortical nodes and where putamic influence on pre-SMA activity was modulated with practice (Fig. 3c). We interpreted this result as suggesting that during multitasking, performance decrements are due, at least in part, to a limit in the rate at which the putamen can excite appropriate cortical stimulus-response representations and that multitasking limits may be remediated by changes in the rate of information transfer between the putamen and the pre-SMA. Therefore, our data do suggest, in accordance with theoretical models of sensorimotor decision making, that the interface between the putamen and key cortical nodes is a putative neurophysiological substrate of multitasking limitations. It must be noted, however, that DCM *does not* test whether modelled connections are direct or mediated by a node not included in the network. Therefore, these results have to be interpreted in light of that caveat.

These differing approaches to studying the neurophysiological substrates that underpin multitasking costs offer a subtly yet importantly different answer to the question of why a complex system like the brain may evolve to be such a poor multitasker. Whereas the *cognitive architecture approach* reviewed above posits that multitasking limits arise from a structural limitation in the system, the concepts arising from the study of the multiple demand and animal sensorimotor systems are instead focused on how a system could operate to optimally learn and solve complex problems. The insight revealed by the *systems architecture approach* is that serial completion of successive subgoals in frontal-parietal-subcortical circuits is a candidate effective method, as is sharing representations in this system between tasks in newer task contexts (see more on this in the discussion below). To wit, these strategies ensure a greater chance of successful performance in complex task spaces. Note that the concept of successive subgoal representation does not necessarily explain multitasking costs per se, as it does not explain why two chains of successive tasks could not be completed at once. On this point, learning and reinforcement models (Sutton and Barto 1998) can potentially provide further insights. For example, when the goal of the agent is to learn by reinforcement, it is important to not overrepresent any task with extraneous information from other tasks. This ensures that rewards only reinforce the exact representations that caused the attainment of reward and prevents the agent over-associating non-causal behaviours to reward gain. Under a purely parallel system, an organism may well attribute reward to all ongoing behaviours and therefore engage in an array of superstitious rituals in order to attain a simple cookie. We return to the concept of task overrepresentation, and how practice may act to reduce it and thereby alleviate multitasking costs, in the final section of this chapter.

5 Neural Architectures: How Models of Neural Functioning Shed Insights into Multitasking Systems

All of the approaches mentioned above have taken observations of either empirical features of multitasking behaviour or neurophysiological signals and from there have deduced what kinds of algorithms could give rise to such multitasking phenomena. The last approach we shall discuss in our taxonomy uses specific knowledge about how neurons function, or are assumed to function, and generates networks that give rise to multitasking costs, typically as a consequence of some other computational feature of the system. For example, by leveraging what we know about synaptic activity, and more specifically the contribution of N-methyl-D-aspartate (NMDA) and α-amino-3-hydroxy-5-methyl-4-isoxazolepropionic acid (AMPA) receptors to whether or not a given neuron fires, Zylberberg et al. (2010) built a spiking neuron network model to perform sensorimotor tasks. Their network comprised local pools of sensory and motor neurons that converged on a common set of integrator neurons. They showed that sensory modules (e.g., the neurons that comprise the processors of sensory information input from different modalities) could maintain and amplify incoming information when receiving non-specific feedback from integrator neurons, i.e. excitatory inputs from integrator neurons act to boost and extend the duration of local, recurrent activity of whichever sensory pool it is feeding back to, thus maintaining a representation of the stimulus in the system, beyond the duration for which the stimulus is actually present. This ongoing activity has been proposed to form the basis of conscious access, or phenomenological experience (Dehaene et al. 1998; Mashour et al. 2020). Subsets of these integrator neurons link sensory and motor pools and receive inputs from task-set neurons (see Fig. 4a). Therefore, the same integrator neurons also serve as detectors of the conjunction of a specific task-relevant stimulus-response pairing. For this model to perform sensorimotor functions successfully, response-execution neurons must inhibit the integrator neurons immediately after the response, in order to maintain a single response mode state and to avoid perseverative errors. The network performed multitasking with the aid of task-setting neurons that, just prior to the presentation of the first task, act to excite integrator neurons that connect the task 1 relevant sensory and motor neurons and to inhibit briefly those integrator

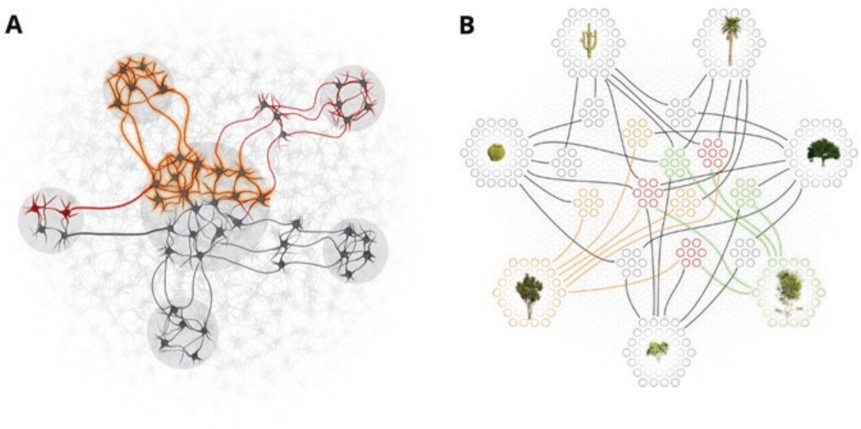

Fig. 4 How modelling the activity of neural networks has leveraged insights into the causes of multitasking limitations. (**a**) According to global workspace models, general-purpose integrator neurons (central pool) send excitatory signals to maintain recurrent activity in local pools of sensory and motor neurons (peripheral pools). Stability of response states requires temporary inhibition of integrator neurons, thereby causing delays to the completion of the second sensorimotor task. (**b**) Overlapping representations in neural network models. Stimulus inputs overlap with hidden processing units to the extent that the stimuli share statistical regularities with one another. The consequent sharing in underlying stimulus-representation results can motivate more rapid learning of new tasks but requires inhibitory mechanisms to control cross-talk in the network. The result is a limit on the number of operations that can be performed at any given time, independent of the size of the network

neurons that connect the peripheral pools for task 2. The construction of this network was an impressive feat, utilising 20,000 neurons and 46,000,000 synaptic connections.

During simulations of task performance, the network showed several features that were characteristic of findings from the empirical literature: First, multiple sensory and motor pools could be active at any given time, which is in accordance with the observation that sensory and motor information can be decoded from associated brain regions in parallel (Marti et al. 2015) and that sensory responses to task 2 inputs occur within a few hundred milliseconds, even when task 1 is underway (Marti et al. 2012; Sigman and Dehaene 2008). Moreover, the model showed that integrator neurons begin sharing information only after 300 ms and that their onset is delayed for task 2. Analogously, the P300, a component that is assumed to originate from frontal and parietal cortices and is often observed in neural signals recorded with high temporal resolution (e.g., MEG or electroencephalography, EEG) during sensorimotor processing, shows a typical onset of around 300 ms and a delayed onset for task 2 (Brisson and Bourassa 2014; Hesselmann et al. 2011; Marti et al. 2012; Sergent et al. 2005; Sigman and Dehaene 2008). Therefore, not only is this model grounded in known principles of neural function, it also generates many of the observed neural correlates of multitasking.

Interestingly, this model and the convergent empirical observations map neatly onto the originally proposed bottleneck model discussed earlier in this chapter, in that sensory and motor processes can proceed in parallel and that delays occur at the information processing stage that maps a stimulus input to the task-relevant output. It also sheds some unique answers into the whys of multitasking limitations. For example, this system is solving the problem of how to maintain internal representations of external sensory inputs, something that is critical in a dynamic environment, and, at a cost, engages an all-purpose recurrent system for maintaining internal activity that acts serially to preserve internal states. Moreover, this model solves the problem of how to integrate information between disparate sources, such as sensory inputs and motoric outputs while maintaining stable internal states. The expense of which is a delayed, serial procedure of routing information between stimulus and response. Note that these explanations for why we see multitasking costs are compatible with the concepts of problem solving, representation, and control that we discussed in the previous section.

5.1 Neural Networks

Recently, insights into the putative neural basis of multitasking have been made via the application of neural-network models to performance of the kinds of tasks that typically give rise to multitasking costs. The emerging picture from this work is that multitasking limits may not be due to some capacity limitation of an underlying neural resource but rather may emerge as a consequence of a network that shares relevant information across task contexts. Neural-network models are biologically inspired learning algorithms whose design is driven by the goal of mapping stimulus inputs to appropriate response outputs. The kind of tasks to which neural networks are typically applied include classification of natural images, natural language parsing, and time-series forecasting (Carpenter 2001; Paliwal and Kumar 2009). Typically, a neural network model consists of an input vector, at least one hidden layer, and an output vector. The input layer reflects ‘neural activity’ invoked by a stimulus input, the output layer reflects the response produced by the network given that stimulus, and the hidden layers reflect the system’s internal representation of the stimulus. Each element of these vectors reflects a neural unit, whose strength of activation is reflected by the value of that element. Each vector connects to another via a weights matrix, which transforms its input into the activity of the next layer, typically via a nonlinear function. These weight matrices can be thought of as reflecting how the network has learned to transform the relevant inputs for representation at the next level in such a manner that the network can successfully represent the input and perform the task correctly. Over multiple iterations, the network is taught (e.g. via back propagation) to adjust these weights to achieve accuracy of performance. Although neural networks do not necessarily reflect the exact computations performed by the brain’s neurons to the same extent as the detailed spiking neuron network we discussed above, they do hold the potential for unravelling insightful and unexpected computational consequences given a system that seeks to transform inputs into correct outputs. For example, as we discuss below, the training of neural networks to perform the simple task of replicating recurring input values, which is assumed to be a proxy for a simple sensorimotor task, has demonstrated how a system may prefer to share representations between stimuli and tasks, insofar as they share featural or statistical overlap, and this holds consequences for the extent to which that system can multitask without performance costs.

If we consider the structure of the world around us, we can immediately see both great variety and regularity. For example, your walk through a forest may be bordered by multiple tree species, each of which bears its own leaf type and fruit, but all consist of trunks, branches, and leaves. It is not too great a stretch of the imagination to assume that it is wasteful for each tree species to be represented by sets of neurons that share no overlap, not to mention computationally impossible given the variety of stimuli in the world. Rather, subsets of neurons could contribute to the representations of multiple trees, according to the degree of featural overlap between exemplars. Such shared representations may potentially garner multiple benefits for any system that has to learn to perform multiple tasks in an information-rich world. It has been shown that the efficacy of machine learning algorithms is improved when a model is trained to simultaneously solve multiple problems from a single input, such as detecting both the gender and the emotional expression from the image of a face, relative to when the algorithm is trained on each task in isolation (e.g., Caruana 1997). Moreover, novel tasks may be learned more rapidly when a new network is initialised with features derived from a network previously trained on multiple tasks (Yosinski et al. 2014). Shared representations motivate such learning by sharing informative features across overlapping tasks. This is protective, in that it prevents a system learning about the idiosyncrasies of incoming data, and it enables the system to develop informed priors over which elements of the new input are likely to contain useful data. Shared representations also support generalisation of learned information to subsequent tasks, resulting in a system that can acquire new tasks with greater ease than a system that does not share representations. Given that a remarkable feature of the human brain is the capacity to perform and learn a great range of tasks, any theory of the neural basis of multitasking that can provide answers as to why cognitive flexibility and limited multitasking capacity coexist as features of the human brain is indeed a compelling one.

It is hopefully clear why concurrently performing multiple tasks may suffer when there is competition for access to shared, underlying representations. Such a trade-off between information sharing and multitasking ability has been demonstrated in neural-network models that have investigated how multitasking limitations may arise, not due to structural limitations but rather as a consequence of the control mechanisms required to maintain task accuracy in a network that shares information across stimulus-response mappings (Feng et al. 2014) or as a consequence of exploiting statistical regularities between tasks to motivate rapid learning (Musslick et al. 2017). In the first, Feng et al. (2014) sought to understand how the extent of information sharing in a neural network may induce a control mechanism to titrate the activation strengths of given task inputs and outputs in order to maintain accuracy of stimulus-response mappings. The resulting activation strengths were taken as a proxy of how well the network could support multiple tasks concurrently. Specifically, the authors constructed a neural network model where pairs of input units were connected to pairs of output units to form a single ‘task pathway’. Pairs of input-output units were selected to reflect neural representations of the two alternative choice tasks commonly used in multitasking paradigms. To simulate the notion of shared representations, input units could not only connect to the output units of their own pathway but also to the output units of other task pathways. These connections instantiate shared representations in the network. The total number of cross-talk connections was varied over simulations, as was the proportion that projected congruent weights to the task pathway with which they were connected. Congruent cross-talk acted to exaggerate the existing activity in the original task pathway. You could imagine this being analogous to seeing a red ‘don’t walk’ light at a pedestrian crossing and a red light for your direction of road traffic. Both stimuli map to the same response of stopping. In contrast, incongruent cross-talk would antagonistically modulate activity in the task pathway. You could imagine a pedestrian starting to set foot onto the road as the traffic light turns green, even though the red ‘don’t walk’ sign is still displayed. As with the incongruent cross-talk, the two signals compete to activate both responses of ‘walk’ and ‘don’t walk’.

The overarching goal of this neural network was for each single task pathway to match the activity values of its output unit pair to the values of its input unit pair, given the provided weights matrix of connectivity and shared representations. This is analogous to forming a correct stimulus-response mapping. To achieve this goal, a control mechanism was able to titrate input and output unit values. This mechanism constituted a vector, each element of which was a constant that scaled the input and output values of the corresponding pathway. The optimal control values were sought that resulted in the minimal mismatch between the activation values from the input and output vectors. Thus, this control mechanism serves to preserve the accuracy of stimulus-response mappings in the presence of conflicting shared representations. The authors interpreted any resulting control values over a given value as reflecting tasks that had received sufficient activation for the task to be performed, i.e. these reflect active task pathways.

Of import, along with simulating the influence of the extent and congruence of cross-talk within the network, the authors also tested the effect of scaling up the network size (the tested range was 10–1000 pathways). This latter point is pertinent given the size of the human brain and the large number of task pathways presumably required to support the goals of an average human. Interestingly, the simulation results revealed the following key features: as the proportion of incongruent irrelevant connections increased, the number of simultaneously activated task pathways reduced. Indeed, as the network size increased, so did the rate of drop-off for simultaneous activations. In fact, regardless of the network size, the number of simultaneous active pathways converged to be approximately the same, when incongruency conditions were high. This result is interesting, because it suggests that even with a very large network, such as the human brain with its ~85 billion neurons (Herculano-Houzel 2009), there should still be a striking and rapidly reached limit in the number of tasks that can be performed simultaneously when cross-talk is incongruent.

The above example shows that shared representations, insofar as they are reflected in cross-connections between input and output nodes of a neural network, can be regulated by a mechanism that preserves the accuracy of stimulus-response mappings by adjusting task activation strength. Although it is relatively easy to mentally deduce that sharing neural representations between common task elements may be a more efficient way for a system to operate, it is far more satisfying when empirical demonstrations uncover exactly what kind of gains may be accrued by a proposed principle of systemic organisation. In a subsequent conference paper, Musslick et al. (2017) make in-roads to directly linking the observation that neural networks learn new tasks more efficiently when sharing representations between tasks (Caruana 1997; Yosinski et al. 2014) to the notion that this comes at the expense of multitasking ability. Again, the authors trained a neural network to map stimulus inputs to given response outputs, although this time the exact mappings were determined by a randomly generated nonlinear function. Importantly, the network was trained to perform nine tasks that mapped to shared output units. Specifically, 3 of 9 tasks would map to a common 5 of the 15 output units. Each task was required to activate only one of its possible five output units, given the stimulus input and the randomly generated function. Thus, this network contained two sources of input: a vector of stimulus input units and a task vector of binary values reflecting which one of the nine tasks was active on any given trial. Each input source was connected to a hidden associative layer by its own weights matrix. Both the associative and the task vectors connected to the output vector via separate weights matrices.

The authors trained the network under conditions that systematically varied overlap between task-relevant inputs and then tested multitasking accuracy as a function of that overlap. At one extreme, tasks relied on entirely separate stimulus inputs, and at the other, tasks that mapped onto different groups of response units were dependent on entirely the same input units. This is analogous to the same stimulus motivating different responses across contexts, for example, the same ball could be kicked or thrown, depending on the requirements of the game being played at the time. By comparing the similarity of vectors from the weights matrix that reflects the learned connectivity between each task context to the associative layer, the authors were able to show that weights for tasks that shared stimulus inputs were more highly correlated than those that did not, even though they mapped to different response outputs. Correlation strength between these weight vectors served as a proxy for the extent of shared representations between tasks within the network.

When the network was required to perform two tasks in a multitask condition, there was a strong negative relationship between strength of shared representations and response accuracy, even though the two tasks to be performed were always mapped onto separate groups of response output units. Therefore, having tasks that share stimulus inputs motivates greater shared representation within the network, which results in a concomitant decrease in the ability to simultaneously perform two tasks drawing from that representation. At first the notion of shared inputs may appear to contradict observations that multitasking costs occur when stimulus inputs and response outputs do not overlap in modality. However, when considering more abstracted levels of the information processing hierarchy (Schmitz and Duncan 2018), it is fairly easy to see how inputs from different modalities would share some statistical overlap and, therefore at some point, can share an input into the circuit that gives rise to multitasking costs. For example, how often does a loud rumbling noise occur in conjunction with the sight of a large motorcycle or motor vehicle?

Musslick et al. (2017) also tested how initialising the network with biases towards shared representations influenced how many iterations it took the network to learn the tasks. Less iterations were required when the task-to-associative layer connections were initially biased towards shared representations (i.e. starting weights were more highly correlated between tasks that shared stimulus inputs), relative to those that were biased against, replicating the finding that covarying internal representations facilitate learning across tasks that can use that representation. Interestingly, the number of iterations required to train the network was not only higher when the network was biased against representational similarity, but this also predicted multitasking accuracy, i.e. networks with lower covarying internal representations learn more slowly and multitask more accurately. Thus, this neural-network model implies that there is a direct trade-off between learning and multitasking. Sharing representations fosters the acquisition of new tasks, at the decrement of multitasking ability. Interestingly, the same research group has also shown that an ideal Bayesian agent will sacrifice multitasking ability that could be achieved over the longer term, by selecting a shared representation scheme to learn tasks more rapidly in order to maximise reward gains in the shorter term (Sagiv et al. 2018), thereby corroborating the notion that more can be gained from organising a system to learn fast and multitask less.

Overall, neural-network models teach us that the neural basis of multitasking may not be due to a structural limitation in long-range information sharing or limitations in the capacity of a central control mechanism (although, given the brain is finite in size, that there is some structural limit to its processing power is a fairly obvious implication) but rather may arise as a consequence of computational features of the network, namely, a network that seeks to maximise learning can, as one solution, share stimulus representations between tasks. This can invoke a requirement to exercise control over the excitation of concurrent stimulus-response mappings. This ensures that particular task pathways cannot dominate network activity due to their co-connectivity profile and consequently reduce stimulus-response accuracy. Therefore, neural network models suggest that attenuated multitasking ability may actually be a consequence of the appropriate application of control. Moreover, where a system can leverage shared statistical structures to more rapidly acquire new abilities, a reduction in multitasking ability may be a necessary trade-off. Thus, neurons that contribute codes to multiple task representations cannot contribute to all task representations at once, without activating inappropriate responses.

This avenue of investigating the neural basis of multitasking is exciting because it leverages focus away from how a capacity-limited processor could exist to give rise to capacity limits in multitasking, a line of thought that runs the risk of restating the problem in more technical terms. Instead this research demonstrates that multitasking limits could instead be a consequence of response regulation and effective learning. We also believe that the shared representations account may shed insights into why multitasking improves with practice, which we turn to below.

6 Shared Representations and the Modification of the Limits of Multitasking: A Novel Perspective

The neural network models above demonstrate how sharing representations across tasks may enable a system to acquire new tasks more rapidly. In our previous work (Garner and Dux 2015), we found that practice (extended learning) may lead to reduced overlap in the neurons recruited to perform each task, thereby increasing availability of computational power, or reducing potential crosstalk, to enable concurrent performance of the second task. The factors that drive this reduction in overlap remain to be elucidated. In this section, we seek to build links between the insights offered by the neural architecture perspective and our observations, which we have accrued from the system architecture perspective. By motivating new hypotheses, we seek to pinpoint the next steps to further our understanding of the neural basis of multitasking. To achieve this, we conducted a formal investigation into how multiple exposures to stimuli over different contexts could drive down shared representations between tasks. We first describe our model conceptually, in the section ‘Reducing shared representations with practice’. We then elucidate the formalisation of our assumptions in the subsequent sections. Readers who wish to skip the technical details can proceed straight from the conceptual overview to the ‘Simulating practice-related reductions in multitasking costs: new insights’ section.

6.1 Reducing Shared Representations with Practice

We assume that shared representations can occur at least in part as a consequence of initial overrepresentation of the task context and that repeated exposures to this context serve to differentiate tasks, thereby reducing shared representations and consequently multitasking costs. Indeed, there is a large literature showing how context/environment influences learning across lower levels of information processing (Bouton 2004; Gershman et al. 2010; Redish et al. 2007). By the task context, we mean everything that co-occurs with the task-relevant stimulus at a given point in space and time. If we once again take a walk through the forest as an example, we

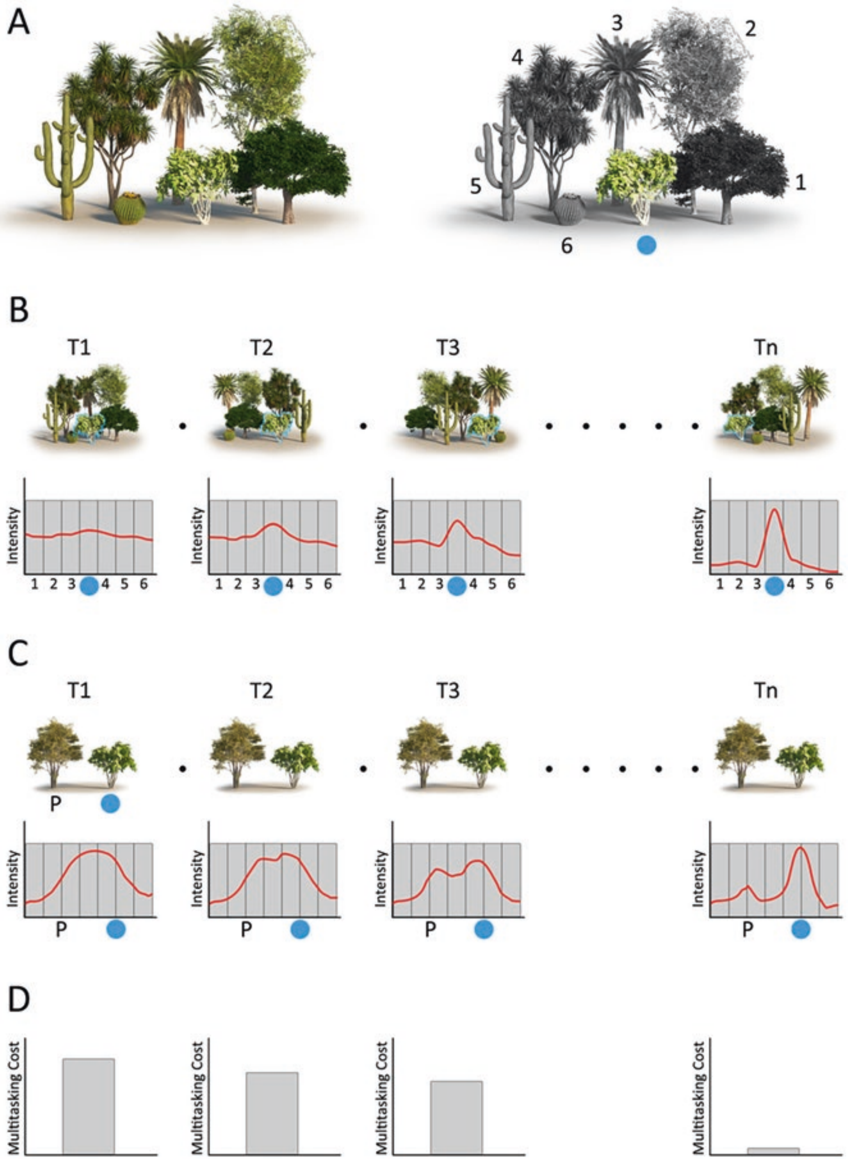

Fig. 5 How practice reduces shared representations and, consequently, multitasking costs. Panel (**a**) A new forest, where the observer must learn about the tree marked with the blue dot (referred to here now as Tree X). (**b**) At first, all trees are relatively new; thus, the observer's model of Tree X is quite undifferentiated from the other species present in the forest. However, multiple exposures to Tree X across a variety of contexts serve to wash out extraneous, nonreliable information, resulting in a representation of the features that are highly specific to Tree X. (**c**) As Tree X is initially undifferentiated from Tree P, the representation of X also serves as a reasonable representation of P. Thus the representations are highly shared and any cognitive operations applied to both will result in multitasking costs (**d**). However, once the representation of Tree X no longer serves as a good model for P, the representations are distinct and multitasking costs are reduced (T = time)

imagine that it is a new forest, full of entirely novel species, and that we seek to learn about one small tree that we know should bear delicious fruit (Fig. 5a). Initially some of the trees will look very similar, for example, two types of trees may share so many common properties that we cannot tell whether they are two separate species or a smaller and larger version of the same thing. Initially, the representation we have of the smaller tree serves as a good enough model for the larger tree (Fig. 5c, first panel). However, as we walk through the forest, we get to see examples of the small tree in a multitude of contexts (Fig. 5b). We learn which other trees are more or less likely to occur with our tree of interest and which of the features are most probable, such as the exact leaf shape or colour. After multiple exposures, extraneous contextual features get washed out so that we have a distinct representation of the small tree. At this point, our representation of the small tree is quite precise and no longer serves as a reasonable model for the large tree. In fact at this point, it appears quite unlikely that they could be examples of the same species (Fig. 5c, last panel). This is the point at which we expect multitasking costs to be most largely attenuated. This is the basic idea behind our model that we specify below.

6.2 Internal Representations of Potential Stimulus Inputs

As we set up our investigation, we'll consider a simpler example than the one outlined above and one that is much closer to a set-up that we would have in the lab. Let's consider a dual-task paradigm consisting of two sensory motor tasks (task A and task B), where each task consists of ten possible stimulus-response mappings. Therefore, across the tasks there are 20 stimuli in total. We also assume that the agent knows that on some trials, one of ten possible coincidental stimuli may occur. In real life this could be something like the experimenter coughing or the light flickering in the lab. As we can instruct a participant as to the nature of the task, we assume that they have some internal model about what they expect to encounter during the task. We refer to this internal model as the internal representations of potential stimulus inputs. We represent this internal model as an $n \times p$ matrix where n reflects the number of possible stimuli to be encountered across the two constituent tasks of the dual task, including both the task-relevant and the 'coincidental' stimuli ($N = 30$), and p the number of featural elements that can be used to code each stimulus. Each dimension of p can be thought of as a sensory quality, such as colour, shape, shadow, pitch, etc. For our current purposes, we assume that each stimulus is encoded with ten features. In accordance with previous observations that higher correlations between internal task representations motivate greater multitasking costs (Musslick et al. 2017; Sagiv et al. 2018), we also sought to investigate whether higher covariance between internal stimulus representations would influence the extent to which representations can be segregated with practice and the consequences this has for reducing multitasking costs. To achieve this, we varied the covariance of the stimulus vectors that make up the internal template over two simulations (i.e., the vectors along n): in the first the stimulus vectors share low covariance with one another, and one where they share high covariance. We therefore construct the matrices so that stimulus vectors are randomly covarying with one another, within the range of $r = [-1, 1]$ for low covariance and [9, 11] for high covariance (these values were randomly selected).

6.3 Matching Stimulus Inputs to Task Templates

For each observation, or trial t, we use a vector $f = \langle f_1, f_2, \ldots, f_n \rangle$ to reflect the encoded stimulus input. Each dimension of the f vector maps to the dimensions of p in the agent's internal template. We assume that the encoding of each dimension of the stimulus vector f is subject to additive noise [$N(0, 0.1)$], that is, to produce f_n, we take the vector that matches the agent's internal template of the randomly selected stimulus and add noise. This serves as the vector that represents the encoded stimulus. We then assume that on every trial, the agent determines which of its internal templates served as the best match for the stimulus input (i.e. response selection). To attain a measure of similarity S between the sensory input f and the internal representations of potential inputs (each n), we compute the reciprocal of the euclidean distance between the sensory input f and the internal template for each stimulus n:

$$S = \frac{1}{\sqrt{\sum_{i=1}^{p} \left(f_i - n_{pi}\right)^2}} \tag{1}$$

6.4 Updating the Agents' Internal Model over Trials

We assume that the agent expects that for each trial t two tasks will be presented and that each task T involves mapping one of ten possible stimuli s to the appropriate response. The agent should therefore construct a model over each task that verifies which stimuli map to that task space, i.e. which stimuli are most likely given the task context (e.g. the context of task B). Let's consider the model for task B; to determine which of the 30 possible outcomes (those for tasks A and B and the coincidental stimuli) are most likely given that the agent is in task B, we can use the Dirichlet distribution, which is a multivariate expansion of the binomial distribution, such that

$$p(s;\alpha) = \mathrm{Dir}(\alpha) = \frac{\Gamma\left(\sum_{n=1}^{N} \alpha_n\right)}{\prod_{n=1}^{N} \Gamma\left(\alpha_n\right)} \prod_{n=1}^{N} s^{\alpha_n - 1} \tag{2}$$

where $\alpha = [\alpha_1, \alpha_2, \ldots, \alpha_n]$ and n is the number of total stimuli, both task related and coincidental. Each α can be thought of as a proxy for the number of times that the stimulus is presented in the context of task A. We assume that the agent begins with no reason to believe that any stimulus will occur more frequently than any other and assume initial uniform priors over all stimuli, i.e. $\alpha_n = 1$. Each time a new stimulus is presented, the agent updates the probability for what stimulus was shown, given the task context. This is done by updating the alpha parameters of the Dirichlet distribution with the similarity value calculated for each stimulus input, such that:

$$\alpha_{n_t} = \gamma\left(\alpha_{n_t} + S_n\right) \tag{3}$$

where γ is the learning rate, which for our purposes, we set $\gamma = .01$, and S_n is the similarity metric between each internal representation and the stimulus input, as defined above.

We also assume that the agent seeks to exploit shared representations between tasks. Specifically, the agent will use the model for task A as an approximation for task B, insofar as task A provides information about B. This is analogous to the small tree serving as a reasonable model for the big tree, at the start of the walk through the forest. This can be quantified using the Kullback-Leibler (KL) divergence measure, which is derived as follows for the Dirichlet distribution:

$$\begin{aligned} KL\left(p\|q\right) &= \log\Gamma\left(\alpha_0\right) - \sum_{k=1}^{K}\log\Gamma\left(\alpha_k\right) - \log\Gamma\left(\beta_0\right) + \sum_{k=1}^{K}\log\Gamma\left(\beta_k\right) \\ &+ \sum_{k=1}^{K}\left(\alpha_k - \beta_k\right)\left(\psi\left(\alpha_k\right) - \psi\left(\alpha_0\right)\right) \end{aligned} \tag{4}$$

where q is the model (or expectations of probable stimuli) over task A and p the distribution over task B (note that β reflects the parameters for q, i.e. task A, and α reflects the parameters for task B).

We quantify the extent of dual task interference as proportional to the extent that p (task B) can be encoded by q (task A). Specifically, we reasoned that multitasking costs would be proportional to the extent that task B can be explained by the model of task A, as this reflects the extent to which a representation of task A can serve as a representation of task B. Therefore, to approximate a duration of multitasking (MT) interference, we need a measure of the extent to which the model over task A can serve to explain task B. To achieve that measure, we take the reciprocal of the KL divergence.

$$MT = \frac{1}{KL\left(p\|q\right)} \tag{5}$$

6.5 Simulating Practice-Related Reductions in Multitasking Costs: New Insights

We started by simulating what happens to predicted multitasking costs (MT) when the agent practices tasks A and B. To recap, tasks A and B are each sensorimotor mapping tasks, where the agent must produce the correct response to one of ten possible stimulus inputs. Practicing this task over time is our analogy for walking through the forest and being exposed to multiple instances of the same tree. For tasks A and B, we assume that the task-relevant stimuli occur on every trial, and where one of ten possible coincidental stimuli occur on every other trial. We reran each simulation 1000 times, to attain confidence estimates on the predicted multitasking costs. We repeated this process separately for internal representations that share high and low covariance, i.e. are more or less likely to be encodable with shared representations. The results are presented in Fig. 6a. As can be seen, this model produces a learning curve that is similar as to what would be expected in a typical multitasking practice study (see Fig. 6b). Interestingly, differences in the extent of covariance between stimulus representations in the internal task set affect the asymptote of the multitasking costs in a largely additive manner and therefore ultimately place a limit on the extent to which multitasking costs can be attenuated. We have observed something similar in our own practice data (Garner et al. 2014). For example, when participants practice single sensorimotor tasks over thousands

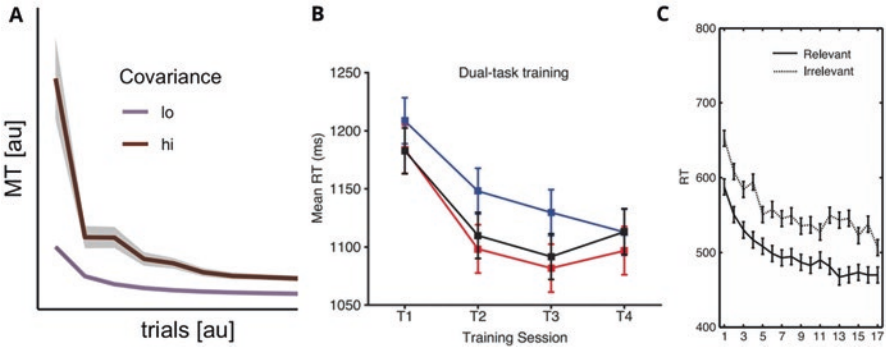

Fig. 6 Model predictions and observed data. (**a**) Multitasking costs (MT) diminish as the task contexts become more differentiated over multiple exposures (i.e. the probability of any given stimulus, given the context of task A, ceases to serve as a reasonable model for the probability of a given stimulus, given the context of task B). Multitasking costs remained higher when the covariance between stimulus representations was high (hi), relative to low (lo). The predicted reductions in MT costs look similar to previous observations, for example (**b**), where participants completed a multitasking paradigm over multiple training sessions under differing brain stimulation conditions (Filmer et al. 2017a, b). Additionally, the observed increase in costs for high relative to low covariances in stimulus representations looks analogous to previous observations that even over thousands of trials, participants take longer to respond to stimuli that potentially share higher covariances (panel C, irrelevant stimuli) relative to those sharing lower covariances (relevant stimuli). Panel C is taken from Garner et al. (2014)

of trials, they are slower when selecting between coloured discs than they are when selecting between letters, and this slowing is additive (Fig. 6c). Although no formal analysis has been applied, it is arguable that the coloured discs were more similar to one another (shared higher covariance) than the letters. However, it is important to note that we have only tested two arbitrarily chosen covariance ranges and further investigations are necessary to see if this observed relationship holds over multiple covariance contexts. Moreover, we have only considered a scenario where there is no stimulus overlap between tasks A and B. Task sets and consequent stimulus displays are typically more complex, consisting of multiple stimuli and features, some of which are relevant across task contexts. For example, a target may be presented inside a circular placeholder in both tasks A and B or the upcoming presentation of both tasks may be preceded by a common alerting cue. It would be interesting to determine the extent to which overlapping contexts influence the extent to which the experience of task A can serve as a model for task B and the consequent impact for multitasking costs.

Our model shows that multitasking costs between novel tasks may be due at least in part to an initial and extraneous oversharing between the multidimensional encoding of sensory inputs to response outputs. Specifically, initial uncertainty about the task space can result in the leveraging of alternate encoding routines, insofar as they provide a sufficiently useful model for current task performance. Interestingly, this investigation makes new predictions; multitasking performance improvements should occur as a function of the *ongoing* covariance between task spaces, and asymptotes reached in response to stable task states should be a linear function of the covariance between feature dimensions used to encode the tasks. Given the potential additive nature of the relationship between task covariances and performance asymptotes, we postulate that perhaps multitasking costs can be related in a novel way to the Hick-Hyman law of decision time (Hick 1952; Hyman 1953). This law states that the time taken to perform a sensorimotor task is a negative linear function of the information offered (in bits) by the stimulus. Here we suggest that multitasking costs may be a positive linear function of the information offered between task spaces. It remains to be determined what constitutes a unit of information in the brain's representation of the task space, and we return to this point in the conclusions below.

7 Conclusions and Future Directions

In our taxonomy of the investigations into the neural basis of multitasking, we have found that there are three broad approaches to tackling this question, pertaining to whether theorising occurs at the level of *cognitive*, *system*, or *neural* architectures. The first involves taking proposed cognitive architectures and seeking to map them to observable neural correlates. The second uses observations of systems-level neural activity to ask how a system that shows those features could perform tasks that incur multitasking costs. The third involves building networks of neural-like or neural-inspired units and seeking how multitasking costs arise as a consequence of the computational features of the system. These approaches have yielded multiple insights into the how and why of the neural basis of multitasking. Here we now seek to highlight points of convergence and disparity between the three approaches and identify the next steps required to further our understanding, using Marr's (1982) levels of understanding as our framework for discussion.

7.1 Understanding Why: What Problem Is the Brain Trying to Solve?

Interestingly, understanding the why of multitasking limitations and their neural underpinnings is difficult to pin down definitively. Just as the interrogation of the neural basis of multitasking can occur at multiple levels of analysis, from verbal descriptions of cognitive stages down to the formalised actions of synapses, so too can the answer as to why the brain so often shows multitasking limitations. For example, the implications of the central bottleneck model are that the brain is limited at certain stages of information processing, which, while evidently true, does not shed insights into why the brain shows such limitations. Indeed, sometimes this literature is interpreted as suggesting that this limitation may be undesirable and should be viewed as something to be overcome (Maquestiaux et al. 2008, 2010). Multitasking costs increase with aging (Maquestiaux et al. 2004), and multiple efforts have been leveraged at attenuating them in older adults (Anguera et al. 2013; Maquestiaux et al. 2004; Strobach et al. 2012a, b). Meanwhile, proposed 'executive' algorithms such as task scheduling or resource management imply that multitasking costs are evident in human behaviour because this is the optimal way to ensure successful task completion in complex environments. The notion that multitasking costs may result because the brain has opted to optimise for something other than multitasking performance is echoed in models of complex problem-solving and network models that seek to mimic multitasking costs, that is, according to the former, complex problems are best solved by being broken down into subroutines that are executed sequentially; however, why exactly some subroutines cannot be executed concurrently remains to be elucidated. Note that these models were never developed to explain why multitasking limits exist, but why they may be applicable remains evident. What network models that seek to mimic multitasking costs tell us is that a neural network that shares information across task representations will learn new tasks more quickly and may even accrue greater reward over the long term, relative to a system that has engaged in parallelism. Moreover, the notion of multitasking costs stemming from shared underlying representations suggests that multitasking costs may be a necessary function of a system that builds internal models of a world that contains statistical dependencies. Thus, the expense of our remarkably flexible, accurate, and adaptable behavioural repertoires may be the capacity to multitask without cost.

7.2 What Are the Computational Algorithms Underlying Multitasking Performance?

Of the proposed and implicated computational algorithms discussed in this chapter, we see two key emergent themes in relation to multitasking, those of *organisation* and *representation*. Central executive models stemming from the *cognitive architectures* approach imply that multitasking costs emerge when a system is required to schedule access to functional modules that perform elements of constituent tasks. Thus, multitasking occurs as a function of scheduling. The notion of subroutines is indeed a pervasive one across investigations into aspects of cognition that require some element of control (e.g. Duncan 2010; Meyer and Kieras 1997b; Roelfsema et al. 2000). The study of *system architectures* has suggested that a common frontal-parietal system may encode the contents of the current subgoal and that a serial processing strategy may act to preserve the appropriate response required to attain that subgoal. Thus, multitasking costs stem from the sequential suppression of competing responses. Moreover, given that both the study of *system* and *neural architectures* implies that a common pool of neurons are recruited to encode the current subgoal, a serial representation strategy may arise in order to preserve the integrity of representations. Any flexible and adaptive system requires a method to ensure that subgoal representations remain distinct, which would no doubt be challenging when units capable of representing any subgoal are concurrently recruited to represent multiple subgoals. Taken together, these findings imply that multitasking costs may play a role in the preservation of causality judgements. For example, if two actions are selected in parallel, how would a system apply sensory feedback to credit which action caused the successful attainment of each subgoal? Rather, by ensuring a schedule of response selection, sensory feedback can be credited to the action with a greater likelihood of accuracy. Whether this is indeed the case remains an open question.

Another point of convergence between the system and neural architecture approaches is the finding that systems are likely to share information between task *representations*. There is broad support that the brain gains representational efficiency by sharing representations between tasks and that this occurs at the direct expense of multitasking capacity. In the case of the systems approach to the study of human cognition, the emerging picture is that the subcortical and associative cortices contain neurons that carry information regarding current task set rules, across multiple tasks, i.e. an internal model of the current statistical dependencies is required to perform a given subgoal. At first it may appear perplexing that given the exact number of neurons in this scenario, we could reach a point of hardware overload that could induce multitasking costs. Interestingly, what we have found from the application of neural network models is that a system of any size that shares information between processing units (i.e. neurons) will converge on being able to perform only a few tasks simultaneously. Thus, a system that shares information between tasks achieves flexibility and adaptability, but this occurs at the expense of parallel processing. These findings therefore imply that statistical dependencies between task contexts provide a hard limit on multitasking performance when a system engages in information sharing. What remains to be discovered relates to exactly how a system may represent a task space that enables information sharing. Specifically, what are the dimensions along which the brain encodes task states? Which dimensions impact most on information sharing and, hence, multitasking? Is information sharing between tasks determined by continuous or piecewise functions? The answers to such questions will not only provide further insights into the neural basis of multitasking but also the representational units that make up the neural states that support adaptive cognition.

7.3 What Are the Physical Implementations of These Algorithms?

Investigations into the neural architectures that underpin multitasking performance have yielded promising advances for understanding potential hardware implementations of the observable cognitive phenomena. Models of neural architectures containing biologically plausible synaptic dynamics have shown how neurons may integrate information between sensory modalities and how successful integration may require a serial processing strategy. The next exciting steps are to extend neural network architectures that support shared representations to implement neurophysiologically plausible rules for synaptic dynamics and to determine whether multitasking capacity is similarly rapidly attenuated in such a system. This would link a physical implementation to a putative algorithm that drives multitasking limitations, namely, the transformation of high dimensional data (i.e. all incoming sensory data from the environment) into latent factors that describe the external world and thereby multiple task contexts, in a lower dimensional space. According to this view, units representing shared latent factors will cause greater multitasking costs than those that do not. Demonstrating a biologically plausible architecture that instantiates these principles would be an exciting and critical advance for the shared representations theory.

The effort of understanding the hardware implementation of multitasking operations can also be informed and constrained by the insights offered by the cognitive and system architecture approaches. For example, the LPFC has consistently been implicated as one site of potential importance. We may be able to next identify whether the LPFC neurons that appear to represent information pertaining to constituent tasks differ from their neighbours in terms of genetic expression, structure, connectivity, and dynamics, which will motivate new inferences regarding the capacities of a system that incorporates these elements into its computational principles. Beyond the LPFC, investigations have largely shown that a set of distributed frontal-parietal brain regions and the striatum have been linked to multitasking costs. The striatum contains multiple cell types, containing differing dopamine, cholinergic, and GABAergic receptors (Tepper and Plenz 2006) that have been linked to various modes of learning, such as prediction error updating and classical conditioning (Cox and Witten 2019). Future investigations can leverage these observations to make formal links between the logic underlying synaptic dynamics and representation sharing in the interface between the striatum and the cortex. Such efforts, while enormously challenging, will hopefully feedback to constrain putative mechanisms of neural computation, thereby making the next critical steps required for understanding the neural basis of multitasking.

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The Contribution of Functional Brain Imaging to the Understanding of Cognitive Processes Underlying Task Switching

Marcel Brass and Wouter De Baene

1 Introduction

Brain imaging research in the domain of task switching can be seen as an interesting example of how classical cognitive psychology interacts with cognitive neuroscience when investigating a specific phenomenon. In contrast to other domains, where an extensive cognitive literature already existed when functional brain imaging became a widely used research tool (e.g., research on memory or perception), task switching only became a "hot topic" in cognitive psychology in the mid-1990s almost at the same time when brain imaging was introduced to cognitive psychology (for a review of the cognitive literature, see Koch & Kiesel, Chap. 3, this volume). Hence, brain imaging research on task switching only lagged a few years behind behavioral research on this topic. The first published attempts to investigate task switching with fMRI date back to the early 2000s (e.g., Dove et al. 2000; Kimberg et al. 2000). Interestingly, brain imaging research in task switching started with a strong neuroanatomical hypothesis that was based on neuropsychological research on cognitive control (e.g., Shallice and Burgess 1991). Using neuropsychological tests such as the Wisconsin Card Sorting Test (WCST), it was demonstrated that patients with prefrontal brain damage, in particular in the lateral prefrontal cortex, show deficits in cognitive flexibility (Anderson et al. 1991). In the WCST, participants are asked to sort cards according to various stimulus dimensions. The

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valid sorting principle is changed without explicit warning, and the participants are required to detect the new valid rule by trial and error. However, the WCST was clearly not a process-pure measure of cognitive flexibility but rather confounded a number of cognitive operations such as sensitivity to feedback and the requirement of exploring the task space (Nyhus and Barcelo 2009). While brain imaging work on the WCST tried to solve these problems by simplifying the paradigm (e.g., Nagahama et al. 2001), the task switching paradigm seemed to be a promising experimental alternative to investigate the brain correlates of cognitive flexibility. In contrast to the WCST, task switching paradigms did not require participants to identify the relevant task set via trial and error but rather clearly indicated which task to execute either based on the task sequence (Rogers and Monsell 1995) or based on task cues (Meiran 1996). Furthermore, by comparing switch and repeat trials, the paradigm provided a perfect contrast for brain imaging research which was in the beginning completely based on the subtraction logic (i.e., comparing brain activation between two conditions to isolate a specific cognitive process). While the early brain imaging research on task switching was primarily searching for a ‘switch area’, later research has more specifically tried to use fMRI to understand the cognitive processes underlying task switching.

In addition to fMRI, task switching has also been investigated with EEG (e.g., Nicholson et al. 2005) and in neurological patients (e.g., Woodward et al. 2002). However, this chapter will primarily focus on the fMRI work that has been carried out with the task switching paradigm (see also Richter and Yeung 2014, for a similar review). We will focus on the most paradigmatic studies and not try to cover all the literature. Furthermore, we will try to address the question to what extent brain imaging research on task switching has contributed to our understanding of the cognitive processes underlying task switching. Hence, the primary aim of the current chapter is not to address the question of which brain regions are involved in task switching. Nevertheless, evaluating the contribution of brain imaging to our understanding of the cognitive processes that are involved also requires to some degree a discussion of the functional neuroanatomy of task switching. It is crucial, for example, to distinguish brain areas that are specifically involved in task performance from “domain general” brain areas that are involved in cognitive control. However, we will try to keep the functional neuroanatomical part as simple as possible and will not go into much detail regarding functional neuroanatomical distinctions as long as they are not important for the understanding of the underlying cognitive processes.

Two major approaches to investigate task switching with fMRI can be distinguished and will be separately discussed in this chapter. First, classical univariate approaches to analyze fMRI data have been used to investigate which brain regions are related to specific component processes involved in task switching (e.g., Brass and von Cramon 2004; Braver et al. 2003; Dove et al. 2000; but see Wylie et al. 2006, for an alternative approach). With the advent of multivariate techniques to analyze fMRI data and the use of repetition suppression, a different approach has become more widely used in recent years. This approach investigates task switching on the task representational level (e.g., De Baene et al. 2012b; Haynes et al. 2007;

Qiao et al. 2017). In the current chapter, we will take a largely "historical" approach to give an overview of the relevant literature. We will first review the literature that has used a classical subtraction logic to investigate the neural correlates of component processes involved in task switching and then review the literature that has looked at the representational level. In addition, we will also cover more specific areas in the task switching domain such as language switching and voluntary task switching.

The interaction between the behavioral literature on task switching and the brain imaging literature has always been rather asymmetrical. Brain imaging studies in this domain were often motivated by observations and paradigms from the behavioral literature that were then investigated in the scanner without necessarily addressing the same type of questions that motivated the experiments in the first place. Often the aim of brain imaging research has been the anatomical localization of processes rather than dissociating processes or further investigating their functional properties. Furthermore, the level of experimental sophistication that dominated the behavioral literature (see Koch and Kiesel, this volume) could not be matched in brain imaging. The behavioral literature on task switching usually has not referred much to the brain imaging literature besides general statements regarding the role of the prefrontal cortex. Hopefully, with some temporal distance, it is easier to evaluate the contribution of brain imaging to our understanding of the cognitive processes involved in task switching.

2 In Search for a "Switch Area"

Early brain imaging research on task switching tried to identify activation in the prefrontal cortex that was stronger for switch compared to repetition trials. One of the first published studies that used the task switching paradigm to investigate cognitive flexibility with fMRI was carried out by Anja Dove at the Max Planck Institute for Human Cognitive and Brain Sciences in Leipzig (Dove et al. 2000). In this paradigm, a simple response-reversal task was used where participants were instructed to respond to one stimulus with a left response and to the other stimulus with a right response. After a few trials, a color change cued the reversal of the stimulus-response (S-R) mappings, constituting a switch trial. Switch trials were always embedded in a sequence of repetition trials. Furthermore, inter-trial intervals were long enough to ensure that the BOLD response could return to baseline enabling a trial-related analysis. When comparing the infrequent switch trials with the more frequent repetition trials, a network of brain regions showed stronger activation for switch versus repeat trials. This network included frontolateral regions, the SMA/preSMA, parietal cortex, the anterior insula, the precuneus, and the thalamus. The study seemed to support the idea that lateral prefrontal regions are crucial for cognitive flexibility, but other brain regions were involved as well. Furthermore, the study also demonstrated that this network was not only active for switch trials but also showed above baseline activation for repetition trials. Here, a first discrepancy occurred with existing cognitive models of task switching, in particular with the reconfiguration model of task switching (Rogers and Monsell 1995). The reconfiguration model assumed that task reconfiguration should only occur in switch trials but not in repetition trials. If brain activation reflected such a reconfiguration process, it should not occur in repetition trials. While these findings were encouraging regarding the use of task switching paradigms to investigate cognitive flexibility with fMRI, the study also had some shortcomings that limited the interpretation of the results. First, switch trials were embedded in a sequence of repetition trials resulting in an uneven number of switch and repeat trials. Hence, brain activation for switch trials could not only be attributed to a switch operation but also to a kind of surprise response. As we will discuss later in more detail, the switch proportion has an important impact on switch-related brain activity (De Baene and Brass 2013). Secondly, the response reversal task that was used in this first study differed from most behavioral task switching paradigms where clearly distinct tasks were introduced. One other study was published at the same time (Kimberg et al. 2000) using the alternating runs paradigm of Rogers and Monsell (1995) to investigate switch-related activity. In addition, this study tried to separate task preparation-related activity from task execution-related activity. Unlike the study by Dove and colleagues (2000), this study had an equal number of switch and repetition trials and also used more complex tasks. Interestingly, this study only identified switch-related activity in the parietal cortex at the time of stimulus presentation. No switch-related activity was found in the preparation interval.

3 Decomposing Task Preparation and Task Execution

In an attempt to dissociate preparation from execution-related brain activity in task switching, Brass and von Cramon (2002) used a classical cuing paradigm (Meiran 1996) and a manipulation of the cue-target interval. In their study, relatively abstract tasks were used (i.e., categorizing the parity or the size of a number). Furthermore, they introduced cue-only trials in which only a cue but no target was presented. This way it was possible to unambiguously isolate cue-related from target-related brain activity. Surprisingly, Brass and von Cramon (2002) did not observe any switch-related brain activity for cue-only trials. However, when contrasting brain activation for the cue with a low-level baseline, strong activation was found in the frontoparietal network previously identified by Dove et al. (2000) both for switch and repeat trials. Brass and von Cramon (2002) concluded that there is strong preparation-related brain activity which however does not differ between switch and repeat trials. Furthermore, this study indicated that in a paradigm where the proportion of switch and repeat trials is equal, it is difficult to identify switch-related brain activation. This conclusion was strongly supported by a study that manipulated switch probability in a cued task switching paradigm (De Baene and Brass 2013). The authors found switch-related differences for task preparation in the frontoparietal network when the proportion of switch trials was low but to a much lesser degree when it was high. They concluded that in blocks where the switch proportion was high and unpredictable, the task set of trial n-1 is not maintained, and therefore configuration of the task set is equally strong in switch and repeat trials. However, when the switch proportion is low, it makes sense to keep the task set of the previous trial active, because it is very likely that it is required in the current trial. Consequently, in this situation, participants have to configure the task set in switch trials but not in repeat trials leading to strong switch-related activation. Hence, the switch proportion can explain the heterogeneous results regarding switch-related brain activation (i.e., why Dove et al. (2000) found strong switch-related activation while Kimberg et al. (2000) did not).

Rather than investigating task preparation with explicit task cues, one can also manipulate whether the upcoming task set is predictable or not (Dreher et al. 2002; Sohn et al. 2000). In a predictable task sequence, one can prepare the upcoming task, while this is more difficult in an unpredictable task sequence. Dreher et al. (2002) found anterior medial prefrontal cortex, hippocampus, and posterior cingulate cortex to be more active for predictable compared to unpredictable task sequences reflecting a network that differs from classical cued task switching studies. In Sohn et al. (2000), foreknowledge of the upcoming task was associated with frontolateral and parietal brain activation. Activation in these areas was also slightly stronger in switch than in repeat trials.

A completely different approach to investigate task preparation in task switching was taken by Sakai and Passingham (2003) and Wylie et al. (2006). These authors investigated whether participants activate task-relevant areas in the preparation interval. Sakai and Passingham (2003) observed different brain areas to be activated in task preparation when participants had to prepare a verbal compared to a spatial task. The only area that was active for both tasks in the preparation interval was the anterior frontolateral cortex. Wylie et al. (2006) and colleagues used tasks that were easier to localize (i.e., a color processing task and a motion processing task). Interestingly, they observed that participants activated color processing areas when preparing the color task but not motion processing areas when preparing the motion task. The failure to prepare for the motion task as indicated by the brain imaging data was also reflected in the reaction times. Hence, these findings suggest that task preparation involves the activation of the relevant task modules. In addition to these task-specific preparation processes, participants also involve domain general brain areas in task preparation, presumably reflecting processes such as general goal setting.

To summarize, different approaches demonstrate that task preparation is associated with a set of frontoparietal brain regions as well as task-specific brain regions, indicating that participants activate the relevant task set when preparing for a task. However, evidence for switch-specific task preparation is rather weak. Again, results from brain imaging research are inconsistent with the general idea that preparation-related reduction of switch costs reflects an advanced preparation process occurring primarily in switch trials.

4 Switching Versus Mixing Costs

A very important distinction in the behavioral literature is the distinction between switch costs and mixing costs (Koch et al. 2005; Rubin and Meiran 2005). While switch costs reflect the difference between switch and repeat trials in blocks where tasks are mixed, mixing costs refer to the difference between repeat trials in mixed blocks and repeat trials in pure blocks where only one task is presented. The basic idea is that in switch blocks, even repeat trials are “contaminated” by the other task that has to be performed. In a seminal study, Braver and colleagues (2003) investigated this distinction with a hybrid event-related and block design. They could show that transient changes between switch and repetition trials activated the previously described frontoparietal network, while sustained brain activity in mixed blocks compared to pure blocks was related to regions in the anterior medial and lateral prefrontal cortex. This sustained activity seems to be independent of the tasks involved (Abou-Ghazaleh et al. 2020). These findings support the idea that switch costs and mixing costs are based on different neurocognitive mechanisms. While the frontoparietal network is involved in the trial-by-trial updating of task representations, the anterior prefrontal cortex overlaps with brain regions that have been related to the so-called branching (Koechlin et al. 1999). Branching refers to the cognitive process that is necessary when a specific task goal has to be maintained while another task is executed. Here, the dissociation on the neural level is taken as evidence for a process dissociation. We will see later that this logic has been repeatedly applied in brain imaging studies on task switching and might be a promising approach for a unique contribution of brain imaging to our understanding of task switching.

5 Stimulus-Based Interference in Task Switching

The early behavioral literature on task switching was dominated by the controversy whether switch costs primarily reflect a task-set reconfiguration process (Rogers and Monsell 1995) or were caused by the so-called task-set inertia, reflecting interference from the previous task set (Allport et al. 1994). One potential source of task-set inertia is the association between stimuli and task sets (Waszak et al. 2003). If a task has been applied to a specific stimulus, this stimulus becomes associated with the task set and triggers this task set when it is presented again. Furthermore, an association between the stimulus and the relevant response in this task set is formed. In switch trials, this association causes more interference than in repetition trials, because the alternative task has been carried out on the stimulus-set in the previous trial. There are two possibilities to investigate this phenomenon. On the one hand, one can compare stimuli that have been associated with two task sets with stimuli that have only been associated with one task set (Waszak et al. 2003). Alternatively, one can also look at the so-called task-rule congruency effect (Sudevan and Taylor 1987), where trials are compared in which a stimulus leads to the same response in both tasks (congruent trials) with trials where the stimulus leads to different responses in both tasks (incongruent trials).

Wylie et al. (2004) compared a situation where a stimulus type was only associated with one task with a situation where the same stimulus type was associated with two tasks. They found that areas associated with the nonrelevant task were activated when a stimulus was presented that had been associated with this task before; hence, the stimuli activated the nonrelevant but associated task set. Furthermore, they demonstrated that when participants had to switch between two tasks where the stimuli were only associated with one task set, switch-related activation in frontoparietal regions was much weaker than in a situation where participants had to switch between tasks where the stimuli were associated with two task sets. They concluded that neural switch costs might be strongly related to resolving task interference that is induced by stimulus-task associations in a task switching context. A similar approach was applied by Crone et al. (2006). In their experiment, participants were instructed to apply two stimulus-response mappings to the same two stimuli (bivalent mappings, e.g., mapping A, press right if you see house and press left if you see a tree; mapping B, press right when you see a tree and press left when you see a house). Which mapping participants had to apply was indicated by a cue that was presented before the target. In addition, participants also had to respond to stimuli that were only associated with one S-R mapping (univalent mapping, e.g., press left if you see a flower; press right if you see a car). The authors found that a large frontoparietal brain network was active when comparing switch and repeat trials for bivalent mappings. However, much less activation was found when switch-related brain activation was compared for univalent mappings. Both studies suggest that switch-related brain activation seems to strongly depend on whether the stimuli are associated with one or with two tasks. Interestingly, the brain regions that were found to be active to overcome interference in bivalent trials were similar to the brain regions that were activated for task preparation.

6 Integrating Findings on Task Preparation and Stimulus-Based Interference

This leaves us with a quite interesting set of observations. First, studies on task preparation show that frontoparietal areas are strongly activated when preparing a task even though this activation does not seem to be specific for switch trials (at least if the proportion of switch and repeat trials is equal). At the same time, the same brain areas seem to be active during stimulus processing when there is competition between two task sets. This interference-related activation seems to be stronger for switch than for repeat trials.

Ruge et al. (2005) investigated how advanced preparation and overcoming interference from a competing task set during stimulus processing might interact. They started from the observation that when participants had time to prepare the task set (long cue-target interval), switch-related brain activation was largely reduced compared to the situation where participants had no time to prepare the task. From a task-set reconfiguration account, this is difficult to explain because according to the reconfiguration logic, participants have to reconfigure the task set in switch trials independent of the cue-target interval. Ruge et al. examined the strength of activation during cue presentation and target presentation in a restricted set of a priori defined regions of interest, i.e., frontoparietal regions. With this region of interest analysis, they found that in the long cue-target interval, frontoparietal regions were equally activated for switch and repetition trials during the presentation of the cue and less so during the presentation of the target. However, in the short cue-target interval, strong switch-specific activation was found (in the short cue-target interval, cue- and target-related activation cannot be separated). They explained this pattern of activation by arguing that in the long cue-target interval, participants have time to prepare the relevant task set, and therefore stimulus-induced interference from the irrelevant task set does not become effective. However, in the short cue-target interval, participants have no time to prepare the relevant task set, and therefore stimulus-induced activation of the irrelevant task set causes strong interference. To overcome this interference and in order to activate the relevant task set, task implementation processes are more strongly required in switch than in repeat trials. This interpretation of the imaging data marries the reconfiguration and task-set inertia idea of task switching. It assumes that there is a configuration process when participants have time to prepare the task in advance. However, this configuration process does not differ for switch and repeat trials when the proportion of switch and repeat trials is equal. When participants have no time to configure the task set in advance, task-set inertia kicks in, leading to a stimulus-driven activation of the competing task set. This increases the need to configure the relevant task set, resulting in stronger frontoparietal activation in switch than in repeat trials. Again, results from brain imaging led to an interesting hypothesis regarding the functional mechanisms involved in task switching. With fMRI, it was possible to separate processes involved in cue- and target-related processing in a way that is difficult to achieve purely on the basis of behavioral data.

7 Backward Inhibition: Dealing with Interference from the Previous Task Set

One prominent concept in task switching is the concept of backward inhibition (Mayr and Keele 2000), also referred to as n-2 repetition benefit (e.g., Koch et al. 2010). The basic idea is that participants might inhibit the irrelevant task set in switch trials to reduce interference. A way to dissociate backward inhibition from other switch-related operations is to compare task sequences of three tasks (task A, task B, task C). In a task sequence ABA, returning to task A after carrying out task

B should have costs when this task was inhibited in trial n-2. However, in a task sequence CBA, this should not be the case because in trial n-2 task C rather than task A has to be inhibited. Mayr and Keele (2000) demonstrated behavioral costs when comparing the task sequence ABA with CBA and concluded that participants inhibit the previously activated task in switch trials. In an attempt to investigate whether backward inhibition can be demonstrated on the neural level, Dreher and Berman (2002) compared task sequence ABA with ABC (notice that the comparison is different from the one carried out by Mayr and Keele (2000)). Interestingly, they found activation in the right frontolateral cortex and argued that this activation reflects overcoming the inhibition of the previously inhibited task set. Hence, the imaging findings indirectly support the backward inhibition concept on the neural level. However, here functional brain imaging provides only an indirect measure of the process in question and therefore does not provide additional evidence for the functional interpretation of the behavioral data. As will be outlined later, more recent multivariate approaches to analyze fMRI data would have been more suited to investigate this question, because with such approaches it would have been possible to investigate whether a specific task-set representation was inhibited or not.

8 The Role of Cue Processing in Task Switching

Another issue that has been extensively discussed in the task switching literature is the role of cue processing in task switching. This discussion cumulated in the proposal that cue switching might account to a large degree for task switching effects in cuing paradigms (Logan and Bundesen 2003). Evidence for this proposal came from a set of experiments where it was demonstrated that in a 2 to 1 cue to task mapping (i.e., two different cues were assigned to each task), cue switching without task switching led to substantial switch costs. While there is behavioral evidence that contests this interpretation of the results (e.g., Forstmann et al. 2007), brain imaging can directly help to settle this issue. The crucial question is whether cue switching activates the same frontoparietal network that was identified for task switching. If indeed task switching is completely accounted for by cue switching, this is what one would predict. In a study that directly addressed this issue, De Baene and Brass (2011) investigated whether cue switching and task switching relied on the same neural mechanisms. First, they investigated brain areas that are more active for task switch (cue and task switch) than for task repetition trials (cue and task repetition). The classical frontoparietal brain regions were observed. Then, they tested in a region of interest analysis whether these brain regions where sensitive to cue switching (cue switch versus cue repeat) independent of task switching. The frontoparietal network was only sensitive to the change of the task but not to a change of the cue. These findings clearly indicate that cue switching effects are dissociable from task switching effects and are based on different mechanisms. Hence, the “clever homunculus” is not as stupid as assumed by Logan and Bundesen (2003). This finding again exemplifies how imaging can contribute to the functional interpretation of behavioral data. It is relatively common in cognitive psychology to challenge a specific functional interpretation of an experimental paradigm by devising a manipulation that leads to a similar behavioral effect inconsistent with the original interpretation (e.g., inducing switch costs by a cue-switching manipulation). However, this often raises the question whether the behavioral effect is tapping into the same cognitive process as the original manipulation. This question can be relatively easily addressed by simply looking at functional neuroanatomical overlap (e.g., does cue switching involve the same processes as task switching?).

9 How Is Domain General Task Switching?

So far, we have primarily addressed the question of specific processes involved in task switching. However, almost all the research we discussed is based on the implicit assumption that task switching reflects a phenomenon that generalizes across tasks. Task switching research has used highly diverse tasks, ranging from simple perceptual or spatial judgments (e.g., Meiran 1996) to more abstract cognitive operations (e.g., Monsell et al. 2003). However, are similar cognitive mechanisms involved when switching between tasks that require, for example, the categorization of perceptual or spatial features and switching between abstract cognitive operations? Such a question is difficult to address using behavioral measures. Of course, one can take an interindividual difference approach and test whether switch costs correlate between different task switching paradigms. However, it has been demonstrated that correlative approaches using experimental tasks can be tricky (De Schryver et al. 2015). A straightforward functional neuroanatomical hypothesis is that if domain general cognitive control mechanisms are underlying task switching, it should be possible to identify a set of brain regions that is common to task switching paradigms independent of the specific task that is used. For almost two decades, this question has been investigated using within-experimental comparisons of different types of tasks producing mixed results (e.g., Philipp et al. 2013; Rushworth et al. 2002). However, meta-analytic approaches seem to give a clearer answer to this question (Kim et al. 2012; Richter and Yeung 2014; Wager et al. 2004). Kim et al. (2012) carried out a meta-analysis on imaging data to investigate whether different types of task switching paradigms activate a set of common brain regions. They distinguished between three types of task switching paradigms, namely, perceptual, response, and context switching paradigms. In perceptual switching, participants have to switch between different stimulus dimensions or stimulus selection rules. In response switching, they have to switch between different arbitrary stimulus response mappings. Finally, in context switching participants have to switch between different rule types. Overlapping activation for all three types of switching was found in the frontolateral cortex (i.e., inferior frontal junction) and in the parietal cortex (i.e., posterior parietal cortex) indicating that core regions of the frontoparietal network are commonly activated independently of the type of task switching paradigm. These results are generally consistent with two other meta-analyses on task switching (Richter and Yeung 2014; Wager et al. 2004). If one assumes that consistent involvement of specific brain regions in different paradigms reflects common underlying processes, these findings seem to suggest that the task switching paradigm investigates a common underlying set of processes.

10 Beyond Classical Task Switching

10.1 Voluntary Task Switching

In the beginning, task switching was conceptualized as a prototypical paradigm to investigate endogenous cognitive control processes (Rogers and Monsell 1995). However, this view was strongly challenged when it became clear that switch costs can be decomposed in component processes of which most are rather exogeneous in the sense that they are stimulus- or cue- driven (for an extensive review, see Kiesel et al. 2010). As an alternative paradigm to investigate endogenous control in task switching, the voluntary task switching paradigm was introduced (Arrington and Logan 2004, 2005). Here, participants can freely choose between different task sets without external cues indicating which task to execute. In this sense, voluntary task switching is strongly reminiscent of intentional action paradigms where participants can freely choose between different response alternatives (e.g., Waszak et al. 2005). Research on voluntary task switching raises two important questions that can be addressed with brain imaging techniques: First, does voluntary task switching involve cognitive processes that are not involved in classical task switching paradigms? Second, are these mechanisms different from the mechanisms that are involved in choosing between simple response alternatives? Interestingly, there is an extensive neuroimaging literature on voluntary action (Brass and Haggard 2008; Krieghoff et al. 2011). This literature indicates that choosing between different response alternatives leads to a specific activation pattern in the frontomedian and frontolateral cortex. The first voluntary task switching study with fMRI was carried out by Forstmann et al. (2006). In this study, participants had to choose between two or three task sets, or the task they had to execute was determined by the task cue. Stimuli were multivalent. After executing the task, participants had to indicate which task they chose. Then, feedback was provided based on the indicated task choice. Forstmann et al. (2006) observed that freely choosing between different response alternatives led to strong activation of the rostral cingulate zone (RCZ), a region of the medial prefrontal cortex that has been implicated in free choice between response alternatives as well (Brass and Haggard 2008). Furthermore, regions in the parietal cortex were more active when comparing free choice with cued choice. Interestingly, activation in these regions did not scale with the number of choices but only distinguished between choice and no choice. In a follow-up study, Demanet et al. (2013) replicated the observation that the RCZ is involved in voluntary task switching. Furthermore, they demonstrated that activation in the

RCZ is dependent on whether the choice was biased by the trial history or not. The brain imaging results suggest that voluntary task switching primarily involves the RCZ, a brain region that is usually not observed in cued task switching. However, this research also indicates that this activation is independent of whether participants choose between tasks or simple responses.

10.2 Language Switching

Another domain that goes beyond classical task switching research is the domain of language switching. Language switching can be understood as one of the most natural "applications" of task switching with a high ecological validity and has a long history both within the research domain of task switching and outside of it (for reviews, see, e.g., Declerck and Philipp 2015; Kroll et al. 2008). Here, a number of research questions that have been addressed in the classical task switching literature such as domain generality, asymmetric switch costs, the role of inhibitory processes in task switching, and the role of preparatory processes have also been addressed. Furthermore, neuroimaging research on language switching started in parallel with neuroimaging research on task switching.

Bilinguals have a remarkable ability to juggle two languages in daily life. When communicating with others, bilinguals are able to control their different languages, efficiently avoiding language conflicts or unintended nontarget language intrusions while smoothly switching between languages. To assure that the use of the target language proceeds fluently, bilingual language control processes are needed. To study these processes, subjects in language switching experiments typically name a digit or picture in their first or second language, depending on a cue (e.g., Costa and Santesteban 2004). The demands of this language switching paradigm in bilingual speakers have many parallels with those of the task switching paradigm. However, contrary to most task switching studies in which more or less arbitrary stimulus-response mappings are used, language switching studies rely on language-defined response sets in which the associations between the stimulus and the response is fixed for each language and highly overlearned.

Some of the first experimental language switching studies were carried out by Kolers (1966). French-English bilinguals were asked to read text passages out loud. The passages could be entirely in French or English (i.e., pure text) or could alternate between the two languages every few words (i.e., mixed text). The reading speed for the pure texts was faster than the reading speed for the mixed text. Kolers attributed this extra time for the mixed text to the cost of repeatedly switching between languages. In many studies following Kolers (1966), switching from one language to another was found to result in a worse performance than repeating a language (e.g., Declerck et al. 2015; Meuter and Allport 1999). Similar to what happened in task switching research, early brain imaging research on language switching tried to identify brain regions showing stronger activation for switch compared to repeat conditions. Hernandez et al. (2000, 2001) executed one of the first series of fMRI studies on the brain bases of language switching. Different groups of high-proficient Spanish-English bilinguals were tested with a mixed language picture naming paradigm. In the blocked, single language conditions, participants were presented with cues in one language (either Spanish or English) during a particular run. In the mixed language condition, the cue alternated between English and Spanish on successive trials. When comparing mixed language blocks with single language blocks, stronger activation for the mixed language (switching) condition compared to the single language (no-switching) conditions was found in dorsolateral prefrontal cortex.

The findings by Hernandez et al. (2000, 2001), together with the results of eight other imaging studies on language switching, were incorporated in a quantitative meta-analysis by Luk et al. (2012). They successfully identified a set of cortical and subcortical regions outside the classical language network that are engaged when switching between languages. This bilingual language control network involves the bilateral frontolateral cortex (including dlPFC, MFG, and IFG), the pre-SMA, the dorsal anterior cingulate cortex, the bilateral inferior parietal lobules, the basal ganglia, the thalamus, and the cerebellum (for a review, see Abutalebi and Green 2016).

Another striking resemblance between the task switching and language switching literature is the observation of asymmetric switch costs. In both domains, switching from an easier task (or dominant language) to a more difficult task (or less proficient language) results in smaller switch costs than switching in the other direction (Meuter and Allport 1999). In both cases, this asymmetry is taken as evidence for inhibition of the language or task set that was active on the previous trial (Green 1998). Especially in the language switching domain, (language) inhibition has taken a predominant place. This is illustrated by the popularity of the inhibitory control model of Green (1998), which assumes that lexical selection in bilingual speakers involves the inhibition of lexical items belonging to the unintended language. Bilinguals typically have different proficiency levels of their first, dominant language (L1) and their second language (L2). Consequently, the amount of inhibition required for the two languages is asymmetric: Since the baseline activation of L2 lexical items is lower than that of L1 lexical items, not much inhibition of L2 is required when speaking in L1. When speaking in L2, however, L1 lexical items must be strongly inhibited in order to ensure that L2 lexical items are selected (Costa and Santesteban 2004). The focus on language inhibition is also related to the fact that in language switching, the languages that are used have overlapping neuro-anatomical bases (e.g., Rodriguez-Fornells et al. 2002), suggesting that bilinguals must have a very effective neural mechanism to prevent interference between the two languages. In task switching, by contrast, the different tasks to perform often rely on distinct neuro-anatomical bases (see, e.g., Wylie et al. (2006) who explicitly selected tasks with a different neural basis, i.e., a color processing task and a motion processing task). Wang et al. (2007) examined the neural bases of asymmetric language switching in Chinese students who were learning English using a picture naming task. When the direction of switching was not taken into account, higher activation on language switch trials compared to repetition trials was found in bilateral frontolateral cortices, right middle cingulate, and the caudate.

When the direction of switching was considered, quite different results were found. Compared to repetition trials, higher activation was found when switching from L1 (Chinese) to L2 (English) in bilateral frontolateral cortices and left ACC, whereas no areas showed increased activation when switching from L2 to L1. Forward switching (i.e., from L1 to L2) thus showed increased activation in brain regions related to executive control which was not the case for backward switching (i.e., from L2 to L1), suggesting that the involvement of these executive control regions was asymmetric, depending on the direction of language switching.

Given the compelling similarities in the language switching and task switching literature, the question arose whether language switching and task switching rely on identical control mechanisms. Two views have been contrasted (Meuter and Allport 1999). First, one could assume that language switching processes are fully subsidiary to the domain-general executive control processes. According to this view, when bilinguals switch between languages, they engage the exact same control mechanisms as when they are asked to switch between nonlinguistic tasks. Alternatively, one could assume that language switching processes are only partially subsidiary to the domain-general executive control processes. According to this view, bilinguals might have developed control mechanisms specific to language. Several behavioral studies have directly compared task and language switching and found some overlap but also some differences in control processes across both domains (e.g., Calabria et al. 2012; Prior and Gollan 2011).

To examine the overlap between the bilingual language control network and the neural networks engaged by nonlinguistic executive control processes, several neuroimaging studies have directly compared brain activation of bilinguals during linguistic and nonlinguistic switching (for reviews, see Calabria et al. 2018; Tao et al. 2021). These studies showed overlap in brain networks involved in language selection and nonverbal task switching. The exact degree of overlap between the language control network and the executive control network is, however, still under debate. De Baene et al. (2015) compared the neural network engaged in multilingual language switching (using Spanish, Basque, and English) with the neural network underlying multicomponent nonlinguistic switching (using color, motion, and gender tasks) using closely matched task requirements within the same trilingual subjects. Frontolateral, frontomedian, and parietal cortex were commonly active in and contributed similarly across linguistic and nonlinguistic switching. The observed differences between the two domains were related to the precise nature of the two tasks: In language switching, verbal responses were required, leading to areas related to phonological processing to become more active. In task switching, by contrast, button presses were required, resulting in higher activation in dorsal premotor cortex. Although this study showed significant overlap between highly similar brain circuits (see Weissberger et al. 2015, for a similar conclusion), other studies have reported only partial overlap between the language control network and the executive control network (e.g., Branzi et al. 2016; Hosoda et al. 2012). Recent studies suggest that the degree of overlap might be modulated by the proficiency level of the second language of the participants. When second language proficiency is very low, distinct networks seem to be recruited for verbal and nonverbal switching (Anderson et al. 2018). However, when second language proficiency increases and becomes similar to the proficiency of the first, dominant language, the language control and domain-general cognitive control network converge (Mouthon et al. 2020; Wu et al. 2019).

Similar to the attempts in the task switching domain to dissociate preparation from execution-related brain activity, Reverberi et al. (2015) designed a language switching study to explicitly dissociate the neural processes underlying language preparation (or the intention to speak a language) from neural processes involved in language execution by introducing a delay period between the cuing of the language to use and the picture to be named. Language preparation did not engage the bilingual language control network but relied on a set of posterior brain regions, more specifically bilateral precuneus, right superior parietal lobule, and left middle temporal lobe. These regions are assumed to be engaged by more general cognitive control demands. Despite the prior long preparation phase, switch trials did show a higher medial frontal cortex activation than repeat trials in the language execution phase, suggesting that language control processes are active in late stages of language production. These results thus suggest that two different systems are needed to enable language selection during bilingual language production: a more general cognitive control network during language preparation and a language control network during language execution.

Reverberi et al. (2018) took a similar approach to dissociate between brain regions involved in language choice and language execution in a paradigm where bilinguals could freely choose the language to use. The authors showed that language choice predominantly relies on a medial prefrontal region, similar to the region involved in free choice in nonlinguistic domains (e.g., Demanet et al. 2013; Forstmann et al. 2006). This suggests that bilingual language choice relies on domain general processes by engaging the medial prefrontal cortex which is critical for free choice, irrespective of the domain. Additionally, the authors showed that language execution relied on the language control network, suggesting that the same network is involved in language execution, irrespective of whether the language is cued (Cf. Reverberi et al. 2015) or freely chosen by the speaker.

11 Investigating Task Switching on the Representational Level

In recent years, the focus has gradually changed from the use of classical univariate approaches as described above to the use of multivariate techniques and repetition suppression to analyze fMRI task switching data. With this shift came a shift toward investigating task switching on the task representational level (e.g., De Baene et al. 2012b; Haynes et al. 2007; Qiao et al. 2017). Since the concept of "task set" plays a crucial role in our understanding of task switching and theoretical models such as task-set inertia strongly rely on the idea of task representations, methodological advances such as multivariate pattern analysis (MVPA) and repetition suppression provided an important new perspective on the neuroimaging literature of task switching. Previously, the only way to investigate the representational level with univariate methods was to use tasks that have clearly distinct neural representations (e.g., Wylie et al. 2006). However, such an approach can only investigate task representations in task-related areas but not in frontoparietal brain regions that usually do not show univariate activation differences for different tasks. Therefore, new approaches were needed to investigate the representational level of task switching with fMRI. Two rather different approaches can be used to investigate task switching on the representational level, namely, repetition suppression and multivariate approaches. We will first focus on the research using repetition suppression and then outline brain imaging research on task switching using multivariate approaches.

Repetition suppression or adaptation refers to the decrease in neuronal activity when a stimulus is repeated. It is based on the assumption that a decrease of activation when information is repeated as compared to when it is presented for the first time will only occur in brain regions in which that given piece of information is represented (Krekelberg et al. 2006). In studies of human perception, many cortical areas thought to house concrete object representations indeed showed adaptation when these visually presented objects were repeatedly presented (for a review, see Grill-Spector 2006). Similar to the way visual brain areas house representations of concrete objects, both prefrontal and parietal regions are assumed to contain abstract task-set representations. Single-cell studies showed that the neuronal properties in prefrontal cortex are consistent with representing concrete as well as abstract task rules (Wallis 2007; Wallis et al. 2001). Also, parietal neurons reflect abstract rules as was suggested by the finding that these neurons respond selectively to cues for different task rules (Stoet and Snyder 2009).

If prefrontal and parietal regions indeed encode abstract task-set information, it is reasonable to assume that these regions will show neural adaptation when (components of) these abstract task sets are repeated. Starting from this assumption, De Baene et al. (2012b) examined whether preparatory brain activation differences between switch and repeat trials could be better explained by adaptation in repeat trials than by enhanced activation in switch trials, as proposed by the task-set reconfiguration account (Rogers and Monsell 1995). However, since both the adaptation account and the reconfiguration account predict higher activation in switch compared to repeat trials, a common switch versus repetition contrast does not allow to disentangle these two views. Therefore, they examined how brain activation evolves across longer sequences of trials. While a classical task-set reconfiguration view would not predict a differential change of activation level in repeat trials over longer sequences of trials, the adaptation account clearly predicts a decrease of activation with successive repeat trials.

De Baene et al. (2012b) showed that BOLD activation on repeat trials in frontomedian and frontolateral cortex and in parietal cortex gradually decreased with increasing repetition run length. A Bayesian model selection procedure indicated that the adaptation model fitted the data better than the reconfiguration model in these regions, suggesting that the higher preparation-related activation in these regions on switch trials compared to repeat trials is better explained by task-set adaptation on repeat trials than by task reconfiguration on switch trials. This pattern of neural activation across successive repeat trials could, however, also be explained by decreasing interference from the previous task set, as proposed by the task-set inertia account (Allport et al. 1994). To dissociate between the task-set inertia account and the adaptation account, De Baene et al. examined whether longer time between two trials was related to larger activation differences between these trials. This would be in line with the interference account, given the assumption that decay of task set activation is time-dependent (Altmann and Gray 2008). The opposite pattern was, however, observed, suggesting that the reported activation pattern was not a reflection of task-set inertia but of task-set adaptation.

Although the term “switch cost” suggests that differences between switch and repeat trials, whether in performance or in brain activation, reflect additional processes in switch trials, e.g., task-set reconfiguration processes (Rogers and Monsell 1995), several authors suggested that performance differences between switch and repeat trials should be interpreted as a reflection of a facilitated performance on repeat trials instead of a reflection of worse performance on switch trials. According to this view, the difference between switch and repeat trials are more adequately described as a repetition benefit instead of a switch cost (e.g., Dreisbach et al. 2002; Koch and Philipp 2005). The observation that it is adaptation to abstract task presentations in repeat trials that causes the activation difference in preparing switch trials compared to preparing repeat trials supports this view. Interestingly, these findings are also consistent with the observation that neural activity in switch trials is enhanced when the proportion of switch trials is low as discussed above (De Baene and Brass 2013). From an adaptation perspective, this would be predicted because neural activity in repeat trials would decrease when the same task set is presented repeatedly, and therefore the contrast between switch and repeat trials would yield stronger activation.

The study of De Baene et al. (2012b) provided support for the idea that both prefrontal and parietal regions contain abstract task-set representations. Possibly, however, these different brain regions adapt to different task-set components. Using a repetition suppression approach, De Baene et al. (2012a) examined which information is encoded in these brain regions. By selectively repeating the stimulus-response mapping or the task goal, they showed that the task goal was neurally represented in frontomedian and frontolateral cortex and (posterior) parietal cortex, whereas the stimulus-response mapping was represented in pre- and post-central gyri, parietal cortex (intra-parietal sulcus), and frontomedian cortex (SMA). Integration of information on both components was found in the frontolateral cortex (i.e., in inferior frontal junction).

The transition to a representational view on task switching which underlies studies relying on fMRI adaptation is also evident in studies using MVPA methods. Multivariate pattern analysis of fMRI data is used to examine the information coding in spatially distributed BOLD activity patterns. Instead of looking at each voxel separately or averaging the signal across voxels and only considering the overall magnitude of the response, as in univariate analyses, MVPA looks for information carried in the pattern of neural responses across voxels (Haxby et al. 2001). Two main MVPA approaches can be distinguished, which are sometimes used together on the same dataset. Information coding can be tested by using a supervised machine learning algorithm such as a pattern classifier, i.e., decoding (Haynes and Rees 2006) or by comparing the correlation of patterns within object classes to correlations between object classes, i.e., representational similarity analysis (Nikolaus Kriegeskorte et al. 2008).

In the decoding approach, the stimuli or tasks are “predicted” from the activity they elicit. It involves training a classifier on a subset of the data to distinguish between data corresponding to different conditions or classes and using the resulting classifier to predict the class labels of another, unseen subset of the data. Thereby, the classifier tries to detect generalizable systematic differences in the neural response patterns evoked by each condition (N. Kriegeskorte 2011). The decoding accuracy, i.e., the average percentage of correctly predicted class labels, is taken as an indicator of the information content of the region. The underlying rationale of this approach is that if the decoding accuracy of a brain region exceeds chance level, then there must be information about the stimuli or tasks in the activity patterns in that brain area (Chadwick et al. 2012). Whereas decoding provides information on the type of information represented in a brain region, representational similarity analyses (RSA) characterize how these stimulus or task representations are structured (Davis and Poldrack 2013). Such representational organization is indexed by focusing on the relative similarity of the voxel patterns across stimuli or tasks in that brain region. These analyses therefore involve computing the pairwise distances between fMRI activity patterns (Cohen et al. 2017).

Haynes et al. (2007) were one of the first to apply MVPA to investigate task-specific representations. They used a delayed intention task in which participants had to covertly choose one of two possible tasks, namely, addition or subtraction. Predicting whether the subject was covertly intending to perform the addition or subtraction task was possible above chance level from the spatial pattern of signals in frontomedian and frontolateral cortex, although these regions did not show different global activity levels for the two intentions. Haynes et al. (2007) concluded that these regions in medial and lateral prefrontal cortex contain task-specific representations of freely chosen intentions. Several other studies showed that not only internally generated task sets but also cued task sets could be read out using decoding approaches. Woolgar et al. (2011), for instance, applied MVPA to examine the representation of stimulus-response mappings in a cued task switching paradigm. The spatial pattern of activity in frontolateral as well as in parietal cortex (intraparietal sulcus) allowed to decode the currently relevant stimulus-response mapping, suggesting that these brain areas include a strong representation of the stimulus-response mapping rule.

Later studies examined whether task-related representations differ between switch and repeat trials. Loose et al. (2017) found encoding of stimulus-response mapping in frontal and parietal cortex. However, the decoding accuracy of this task-related information was not different between switch and repeat trials. These findings suggest that behavioral switch costs are not related to the representations of stimulus-response mappings in frontoparietal cortex since these neural representations seem largely switch independent. Another study, however, came to the opposite conclusion. Qiao et al. (2017) also found encoding of task-set information in frontal and parietal cortex; however, these task-set representations seemed to be less stable on switch than on repeat trials: decoding accuracy of the task set was generally lower for switch than for repeat trials. This is in line with the observation that performance on switch trials is more error prone compared to performance on repeat trials (e.g., Kiesel et al. 2010). The results of Qiao et al. (2017), contrary to the results of Loose et al. (2017), do suggest thus that behavioral switch costs are related to the frontoparietal task-set representations. These divergent findings could possibly be explained by the fact that subjects needed to switch between different cognitive tasks in the study of Qiao et al. (2017), whereas participants were only required to switch between varying stimulus-response mappings in the study of Loose et al. (2017). These findings suggest that the transition modulation of task-set representations depends on the type of switching (context switching vs response switching), which is in contrast with the univariate findings suggesting that the core regions of the frontoparietal network are activated by switching, independent of the type of switching.

Qiao et al. (2017) also showed, using representational similarity analyses, that task-set representations across consecutive trials are more similar for repeat trials than for switch trials. Furthermore, on a task switch trial, the neural pattern of the task set gradually evolved from being more similar to the no-longer relevant task representation of the previous trial to being more similar to the task representation of the newly relevant task. These imaging results bring together the reconfiguration and task-set inertia idea of task switching by providing neural evidence of a task-set reconfiguration process on switch trials that is hindered by task-set inertia.

As illustrated above, several studies have shown that both cued as well as internally generated task sets are represented in frontoparietal regions. Zhang et al. (2013) examined whether task rule representations differ between cued and freely chosen rules. They reported mixed findings: Whereas the frontolateral and frontomedian cortex only represented freely chosen rules, the premotor and parietal cortex, by contrast, represented both cued and freely chosen rules. Furthermore, the representations in premotor and parietal cortex were context independent: the pattern classifier that was trained on cued rules was able to correctly discriminate between freely chosen rules and vice versa. Additionally, the task rule representations in premotor and parietal cortex remained the same between task preparation and task execution phases whereas the task rule representations in frontolateral and frontomedian cortex were specific to the task preparation phase.

Wisniewski et al. (2016) also compared task representations under free and cued conditions. Contrary to Zhang et al. (2013) who examined stimulus-response mapping representations, Wisniewski et al. (2016) examined more abstract task representations (e.g., mental calculation). These abstract task representations were similar across externally cued and freely chosen conditions in frontolateral, premotor, and parietal cortices.

Similar to the transition modulation of task-set representations, the context sensitivity (cued vs. free choice) of task-set representations seems to depend on the type of switching (context switching vs. response switching).

12 What Has Brain Imaging Research Contributed to Our Understanding of Task Switching?

In the last part of this chapter, we would like to discuss the contribution of brain imaging research to our understanding of the cognitive processes involved in task switching. However, before we do that, we would like to comment on the general interaction of researchers from both domains. With a few exceptions, brain imaging and cognitive research on task switching developed with limited exchange between the two domains. Imaging research has been inspired by behavioral paradigms but rarely got involved in the detailed functional interpretations and hypothesis that mushroomed in the behavioral domain. Behavioral research has referred to brain imaging research in a very general way to justify that the cognitive phenomenon had a brain basis and might have clinical relevance. However, very rarely detailed imaging findings have been taken seriously and have influenced functional hypotheses. This mutual ignorance presumably has a number of reasons. Most importantly, only a few researchers have moved comfortably in both domains. This is presumably due to the fact that the interpretation of imaging data requires a very specific expertise that is difficult to acquire without an imaging background. At the same time, the behavioral task switching literature very soon developed a level of sophistication that one could hardly follow as an outsider.

However, what has brain imaging research really contributed? According to Coltheart (2013), the contribution of neuroimaging to a particular cognitive theory should not be based on the mere consistency of the neuroimaging data with predictions from that theory but on falsifying the predictions of that theory. Since data that are merely consistent with a hypothesis might fail to provide evidence for that hypothesis, a fallacy is putatively committed when one, based on the fact that the data are consistent with a hypothesis, claims that those data show that the hypothesis is true without showing how alternative data could have contradicted that hypothesis or how the data contradicts another hypothesis. Although some imaging studies might suffer from this consistency fallacy, many imaging studies contributed in the Bayesian sense (Cf. Chatham and Badre 2019) in that they have increased the belief in a theory by providing outcomes consistent with that theory or have decreased the belief in a theory by providing outcomes that are difficult to match with that theory.

Early functional neuroimaging studies of task switching focused on the neuroanatomical localization of cognitive processes and tried to find specific "switch areas." In line with lesion studies and single-cell recordings, Dove et al. (2000), for instance, found support for the crucial involvement of lateral prefrontal regions in cognitive flexibility using fMRI. However, the results of Dove et al. provided more than a mere replication of these well-known findings. The study demonstrated that other regions besides lateral prefrontal cortex, mainly in frontal and parietal cortex, were also involved in task switching. The initial focus on localizing cognitive functions and/or representations to neural substrates, which, in the early days, was common across most cognitive neuroscience fields, has provided a critical foundation to go beyond the localization issues and address questions related to the mechanisms underlying specific cognitive processes and the nature of the representations involved in task switching.

A first major contribution of brain imaging to the field of task switching, beyond brain mapping, is the finding that preparatory activation of the relevant task set (both in frontoparietal brain regions and in task-specific brain regions) is not specific to switch trials but is common to both switch and repeat trials (e.g., Brass and von Cramon 2002). The activation difference between switch and repeat trials during task preparation seems to be modulated by the proportion of switch and repeat trials (De Baene and Brass 2013). Contrary to the underlying assumption of the task-set reconfiguration account (Rogers and Monsell 1995), neuroimaging findings thus suggest that configuration of the task set is equally strong in switch and repeat trials when the proportion of switch trials is high. When the switch proportion is low, by contrast, task configuration is only needed in switch trials.

By its ability to separate cue-related processes from target-related processing, neuroimaging findings have also been able to transcend the dominating controversy between the task-set reconfiguration account (Rogers and Monsell 1995) and the task-set inertia account (Allport et al. 1994), which has been difficult to achieve purely on the basis of behavioral data. In line with the task-set reconfiguration idea, fMRI data (e.g., Ruge et al. 2005) has suggested that there is indeed a configuration process when participants have time to prepare the task in advance. Again, whether this configuration process is present in both switch and repeat trials or is restricted to the switch trials depends on the proportion of switch trials. However, when there is no time to configure the task set in advance, the competing task set is activated, triggered by the presentation of the stimulus, which is in line with the task-set inertia account.

Several neuroimaging contributions to the understanding of the cognitive processes involved in task switching rely on the observation of dissociations on the neural level that provide evidence for a process dissociation. For instance, by showing that switch costs and mixing costs are based on different neurocognitive mechanisms (respectively the frontoparietal network and anterior medial and lateral prefrontal cortices), Braver et al. (2003) provided evidence that switch costs and mixing costs indeed rely on different cognitive processes, as was suggested in the behavioral literature (e.g., Koch and Philipp 2005). Similarly, De Baene and Brass (2011) provided evidence that cue switching effects are dissociable from task switching effects and are based on different mechanisms by showing that the frontoparietal network is only sensitive to a switch of the task but not to a switch of the cue. By doing so, they could refute the idea put forward by Logan and Bundesen (2003) that task switching effects in cuing paradigms are mainly caused by cue switching. Studies comparing voluntary task switching with cued task switching have taken the same approach: by showing activation in the rostral cingulate zone (RCZ) in voluntary but not cued task switching, they have provided support for the idea that voluntary and cued task switching rely on different cognitive processes (e.g., Forstmann et al. 2006).

Other neuroimaging contributions have relied on the consistent involvement of specific brain regions across different paradigms that provide evidence for the involvement of common underlying processes within these paradigms. Kim et al. (2012), for instance, carried out a meta-analysis and showed that core regions of the frontoparietal network are commonly activated across perceptual, response, and context switching paradigms. This suggests that domain general cognitive control mechanisms are underlying task switching. Furthermore, linguistic and nonlinguistic switching have been contrasted to examine whether identical control mechanisms are involved in both paradigms. De Baene et al. (2015), for instance, showed an overlap between the bilingual language control network and the neural networks engaged by nonlinguistic executive control processes in highly proficient bilinguals suggesting that language switching processes are subsidiary to the domain-general executive control processes. However, the level of overlap between these networks seem to depend on the proficiency level of the second language of the participants.

To summarize, brain imaging research has contributed to our understanding of the functional processes involved in task switching beyond mere localization of these processes. However, more exchange between the imaging and the behavioral field presumably would have increased the impact of imaging research substantially.

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Part IV
Applications

Multitasking Training

Julia Karbach and Tilo Strobach

1 Introduction

Scientific interest in the question whether and how cognitive performance can be improved by cognitive training has been increasing rapidly over the last two decades. The emerging field of cognitive training research has brought together researchers from many areas of psychology, including (neuro)cognitive, developmental, educational, and clinical psychology, but also researchers from other disciplines, such as medicine or educational science. Consequently, the studies on cognitive training have targeted a variety of cognitive processes, among them working memory, executive functions, perception, attention, episodic memory, or processing speed, as well as multitasking. They have also examined different types of samples across a wide range of ages, typically developing individuals and patients with neurocognitive impairments, as well as developmental or geriatric disorders (for an overview, see Strobach and Karbach 2021).

While it is undisputed that intensive training leads to significant and often long-lasting performance improvements on the trained tasks, the question whether training leads to tangible improvements in cognitive skills not directly trained (e.g., perceptual, attentional, memory, motoric skills) and activities of daily living (e.g., adherence to medical treatment plans, academic performance) is not fully answered. Importantly, addressing how training gains generalize to untrained tasks beyond the training context can contribute to answering fundamental questions of cognitive architecture and learning mechanisms. It also has obvious practical relevance, because many populations, such as children diagnosed with developmental

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disorders or learning disabilities, individuals with schizophrenia, traumatic brain injury, and older adults, may show deficits in core cognitive abilities and thus could significantly benefit from effective interventions (Green et al. 2019).

Since the early 2000s, there has been a particular interest in whether executive functions can be improved by training (Smithers et al. 2018). This research was based on findings that executive functions in childhood are linked to academic achievement, mental health, social functioning, and well-being, both during childhood and, especially, later in life (Moffitt et al. 2011). Thus, it is not surprising that there are many attempts to foster these critical life skills, but their findings are equivocal (Diamond and Ling in press; Redick 2019; Titz and Karbach 2014) and have inspired many heated debates in the scientific community as well as in the press and the public.

In this chapter, we will focus on cognitive training from the perspective of multitasking as a core executive function. Multitasking includes the ability to flexibly switch between two tasks (task switching) and to perform two tasks at the same time (dual tasking) (Koch et al. 2018). Both these abilities are characterized by the need to perform multiple tasks under time constraints so that they cannot be performed in temporal isolation. As a consequence, multiple cognitive processes (such as maintaining, selecting, and updating task rules in working memory, monitoring the current status of a task, and evaluating the task-related outcomes) occur concurrently and are represented simultaneously. Many of these control processes gradually develop over childhood and well into adolescence while declining in older age (for a review, see Wiebe and Karbach 2017).

The focus of this chapter is on multitasking training interventions, including task-switching and dual-task trainings, and their effects on multitasking, as well as other cognitive and performance measures. Our aim is to illustrate the potential range of effects resulting from cognitive multitasking training in different populations, settings, and after different types of multitasking training. That is, we focus on interventions including multiple discrete, cognitive tasks and on learning mechanisms underlying training-related improvements in multitasking. The chapter "Training Based on Multitasking – With a Specific Focus on Motor-Cognitive Multitasking" of Wollesen et al. (this volume) also has a focus on multitasking training, but their emphasis is on multitasking interventions, including at least one motor component task and many continuous rather than discrete tasks. The authors present theoretical conclusions regarding mechanisms underlying improved multitasking performance and methodological recommendations for training designs supporting these mechanisms.

In the following sections, we will illustrate theoretical concepts, methodological approaches, and current findings on multitasking training by first introducing the concept of cognitive plasticity and state-of-the-art methodological approaches to study multitasking training. We then introduce theoretical frameworks for transfer of training followed by an overview of findings on task-switching and dual-task training. We close by illustrating individual differences in training gains and by highlighting the potential of multitasking training in educational and clinical contexts.

2 Cognitive Plasticity

2.1 Theoretical Framework of Plasticity

The idea that cognitive processing can be modified as a response to environmental changes or targeted interventions has a long tradition in psychological research. The potential modifiability of individual cognitive abilities and brain activity has been referred to as cognitive and neural plasticity (Karbach and Schubert 2013). The use of the term plasticity dates back to the nineteenth century and has since undergone considerable changes in terms of definition and contemporary usage (for a review of the history of the term, see Berlucchi and Buchtel 2009), covering most types of change in brain and behavior (e.g., Brehmer et al. 2007; Kelly and Garavan 2005; Kempermann 2006). A few years ago, Lövdén et al. (2010) acknowledged the need for both an operational definition and a sharper conceptual distinctiveness of the term cognitive plasticity that includes a more comprehensive notion of change. They proposed a framework of cognitive plasticity that is based on a demand-supply model and specify a number of preconditions for cognitive plasticity. It is assumed that the brain demonstrates the capability to adapt to changing environmental demands based on current structural constraints on brain function and performance – an ability referred to as flexibility. Thus, if environmental demands cause an imbalance with the current brain supply, for instance, induced by demands on executive functioning required in multitasking situations, the brain will react to this supply-demand mismatch with functional (flexible) or structural (plastic) changes. While flexibility leads to an immediate response of the behavioral system by recruitment of available cognitive functions (i.e., a primary reaction to altered demands within the preexisting range of supply), cognitive plasticity requires a reaction to a more prolonged supply-demand mismatch (i.e., a secondary reaction to prolonged altered demands by changing the preexisting range of functional supply). Thus, true plastic changes can only be expected after a prolonged mismatch between demand and supply that challenges participants just enough to induce the mismatch without overextending them. Based on this reasoning, many training studies have applied adaptive training tasks that constantly adjust task difficulty to individual performances (e.g., the interval to prepare for upcoming tasks is shortened when performance improves and extended when it declines in order to increase or decrease difficulty in task switching).

Taking a lifespan view, age-related deficits in executive functions that are typically present in childhood and older age (Karbach and Unger 2014, 2016) suggest that a mismatch between task demands and functional supply will occur more often in these age groups, indicating that especially children and older adults may gain from a moderate mismatch induced by training interventions targeting executive functions. As a consequence, they will benefit more than younger participants from brain changes in their less efficient prefrontal lobe system (see below).

Executive functions, including working memory, inhibition, and cognitive flexibility (Miyake et al. 2000), subserve many abilities that are essential for important life outcomes, such as academic and vocational performance, health behavior, and social interactions (e.g., Johann et al. 2019; Moffitt et al. 2011). Therefore, the interest in the generalization of training-related benefits beyond the trained task has been growing rapidly. These transfer effects can be tested in tasks that are structurally similar to the trained task but tap the same ability (near transfer: e.g., transfer to focus-switching after training of rule-switching). However, they can also be tested in tasks that tap a different cognitive ability that is related to the trained domain (far transfer: e.g., transfer to working memory after task-switching training). Even though there is no commonly accepted metric of task (dis-)similarity and the difference between near and far transfer is not well-defined and varies across studies, existing evidence generally indicates that near transfer occurs quite consistently, while evidence for far transfer is mixed (see below), even on the meta-analytical level (e.g., Au et al. 2015, 2016; Melby-Lervåg and Hulme 2016; Karbach and Verhaeghen 2014; Schwaighofer et al. 2015).

2.2 Methodological Approaches

There is a well-established methodology for the evaluation of interventions in psychology and education (Schmiedek 2021; Murnane and Willett 2011; Shadish et al. 2002), including cognitive training and particularly multitasking training. The most common design for investigating cognitive training is a study plan including a pretest, a training phase, and a posttest, possibly also one or more follow-up assessments. For the training phase, participants are randomly assigned to training and control groups (ideally active and passive control groups). The length of the training phase varies substantially across studies but usually includes a number of training sessions across a prolonged time period. At pretest and posttest, participants perform a set of tasks tapping the cognitive abilities that are probed for training and transfer effects. This type of design allows to control for a number of potential issues, such as retest and placebo effects or preexisting group differences at baseline.

However, a few methodological issues that may affect different aspects of validity need to be considered (e.g., the use of single tasks as outcome measures of transfer effects; for an overview, see Schmiedek 2021). As Schmiedek (2021) pointed out, optimizing different types of validity (e.g., statistical conclusion validity, internal validity, construct validity, external validity) may also lead to conflicts, because decisions regarding the study design may result in direct conflicts among validity aspects. For instance, maximizing statistical conclusion validity by running a study under strictly controlled conditions in a lab environment may affect external validity. Thus, balancing the different aspects of validity during study design requires to acknowledge the fact that intervention studies often serve quite different purposes. Green et al. (2019) illustrate this point by differentiating between feasibility studies, mechanistic studies, efficacy studies, and effectiveness studies and discuss important differences between these designs in terms of study methodology and the conclusions they allow (see also Cochrane and Green 2021).

Feasibility studies are used to test the viability of new approaches, technological innovations, or applicability to a certain population. Their sample sizes can be small, control groups may not be necessary, and they typically precede the other types of intervention studies. Importantly, the focus is not on demonstrating a causal effect. Mechanistic studies aim at identifying underlying and mediating mechanisms and assess causal effects by testing specific hypotheses based on theoretical models. Their outcome measures may rather serve to identify a specific cognitive process than to demonstrate broad transfer effects of relevance for applied contexts. Moreover, they may also be used to answer general questions regarding cognitive development and the range of its malleability (Lindenberger and Baltes 1995; Schmiedek 2021). The aim of efficacy studies is to show causal effects of interventions as compared to appropriate control conditions (such as placebo conditions). In contrast, effectiveness studies focus on the outcome of an intervention implemented in real-world settings. Typical control conditions are "business-as-usual" or "standard of care," and the focus often lies on variables that include more real-life criteria, the longevity of effects, and potential side effects (Green et al. 2019).

The most commonly used analytical approach in cognitive training studies (controlled pretest-training-posttest designs) is a repeated-measures analysis of variance (ANOVA) with the between-subjects factor *Group* (training, control) and the within-subjects factor *Time* (pretest, posttest). A significant interaction of these factors pointing to larger improvements (pre to post) in the training group than in the control group is usually taken as evidence for reliable treatment effects (ideally without significant group differences at baseline). Individual differences can be analyzed by examining interactions with covariates or by analyzing subgroups (see Sect. 7). However, this approach has some serious limitations, among them the following issues (see Schmiedek 2021): First, the required statistical assumptions might not be met (sphericity, homogeneity of (co)variances across groups), and second, subjects with missing data at posttest must be deleted listwise. Third, analyses are conducted at the single-task level and the unreliability of transfer tasks can bias results. Even if several transfer tasks for the same ability are available, analyses have to be run separately or on a composite score. Fourth, if participants are not randomized to experimental groups and their comparability is not ensured, analysis of covariance (ANCOVA) is often used to adjust for potential group differences at baseline. However, this is not ideal in terms of causal inference, because controlling for pretest scores only leads to an unbiased estimate of the causal treatment effect if the sufficiently controls for all confounding caused by unmeasured variables (Kim and Steiner 2019).

Most of these serious limitations can be solved by adopting a structural equation modeling framework and by using latent change score models (McArdle 2009; see also Könen and Auerswald 2021; Könen and Karbach 2021). These models allow multi-group comparisons (when the sample sizes are large enough) that provide the same information as repeated measures ANOVA, while having many advantages. For instance, assumptions of sphericity and homogeneity of (co)variances are not necessary, and missing data can be handled by parameter estimation based on full information maximum likelihood. Moreover, change can be analyzed using latent factors illustrating what is common to a set of tasks that measure the same cognitive ability and are free of measurement error. Thus, estimates of training effects are not biased by unreliability of tasks, and individual differences in change can be analyzed without relying on unreliable individual difference scores (cf. Schmiedek 2021).

Finally, the models can include multilevel analysis to account for the clustering of participants (e.g., in classes), item response models (e.g., to assess training-induced changes on the level of single item responses), or latent class analysis (e.g., to explore different patterns of gain on a set of tasks). Considering these advantages as well as the fact that these models offer the opportunity to assess individual differences in training outcomes on a much more sophisticated level, it is not surprising that they have become increasingly more common over the last few years.

3 Transfer of Training

Over the last two decades, the "brain training industry" has released numerous applications and tools that promise cognitive enhancement, capitalizing on those striving to improve their cognitive abilities, trying to reduce or counteract cognitive impairments or prevent age-related cognitive decline. Unfortunately, many commercial products are not evidence-based and their effectiveness has not been tested against stringent criteria (but see Strobach and Huestegge 2017). This led to heated discussions about the effectiveness of cognitive training, including multitasking training, not only in the scientific community but also in the general public. This discussion has resulted in massive repercussions for scientific research on cognitive training and certainly mandates a critical examination of the quality of existing evidence for the benefits of executive function training. Despite several recent best practice recommendations (Green et al. 2019; Simons et al. 2016) for evaluating the effectiveness of cognitive training, a comprehensive understanding of how, for whom, and why certain trainings can be effective is still missing.

3.1 Theories on Transfer of Training

While most researchers do not dispute the existence of near transfer effects, it is still intensely debated whether executive function training leads to improvements in loosely related domains (far transfer; Diamond and Ling in press). Theoretical approaches vary in their optimism regarding the possibility of far transfer. More than a century ago, Thorndike and Woodworth (1901) argued in their *identical elements theory* that transfer depends on having shared elements in training and transfer tasks; the larger the number of such shared elements, the greater the likelihood that transfer will occur. In 1989, Singley and Anderson updated Thorndike's theory by suggesting that the relevant elements are rules applying in both training and transfer tasks, while Schumacher and Gentner (1988) pointed to the importance of a structural match between training and transfer task based on the systematicity and the transparency of the correspondence. After an extensive review of previous empirical findings, Schmidt and Bjork (1992) suggested that the most important principle is the overlap of processes practiced during training and required during transfer. Importantly, they point out that this overlap of relevant processes does not necessarily mean that there is an overlap in the training and transfer conditions. Put differently, this theory assumes that transfer can occur when the transfer tasks require one or more abilities that were trained in the practice phase, regardless of the structure underlying the transfer and training tasks. Thus, it is assumed that near as well as far transfer should be possible.

More recently, Anderson (2007) proposed a framework claiming that production rules coordinate exchange between specialized cognitive systems, but they are often specific to a particular task. In contrast, the *primitive information processing elements theory* (PRIMs, Taatgen 2013) assumes that training on a particular task yields a set of operators toward that task. Thus, learning specific cognitive tasks results in the acquisition of general skills as a byproduct of the learning process. These general skills can be applied to different tasks without any need for explicit transfer between tasks. The respective tasks sharing the newly acquired general skills can even be quite different – the theory assumes that they route information through the cognitive system in the same way.

The *cognitive routine framework* (Gathercole et al. 2019) is based on a similar idea. It assumes that during training, participants are faced with new task features that induce unfamiliar and challenging cognitive demands. Thus, there is a need to develop new cognitive routines because existing mechanisms are not sufficient to meet these demands. These newly acquired cognitive routines are considered automated cognitive procedures rather than task-specific strategies. They can subsequently be applied to novel tasks sharing the same requirements. The cognitive routine framework also makes specific assumptions regarding common task features that generate (or impair) transfer of working-memory training that can easily be applied to multitasking training: for instance, transfer to tasks requiring interference control is more likely after task-switching training including the requirement to suppress distracting information, such as tasks with ambiguous stimuli or crosstalk at the response level.

3.2 Current Frameworks for Transfer of Training

Thus, existing models allow very different predictions regarding transfer effects. It is therefore not surprising that reviewing existing empirical evidence in favor and against the effectiveness of cognitive training reveals a striking discord in the field with strong claims and supporting evidence on both sides that seems hard to reconcile. In a recent review, Smid et al. (2020) proposed three key paradigm shifts to facilitate a rapprochement by suggesting effective ways to assess whether and how tailored executive function training can be delivered (see Fig. 1): (1) identifying

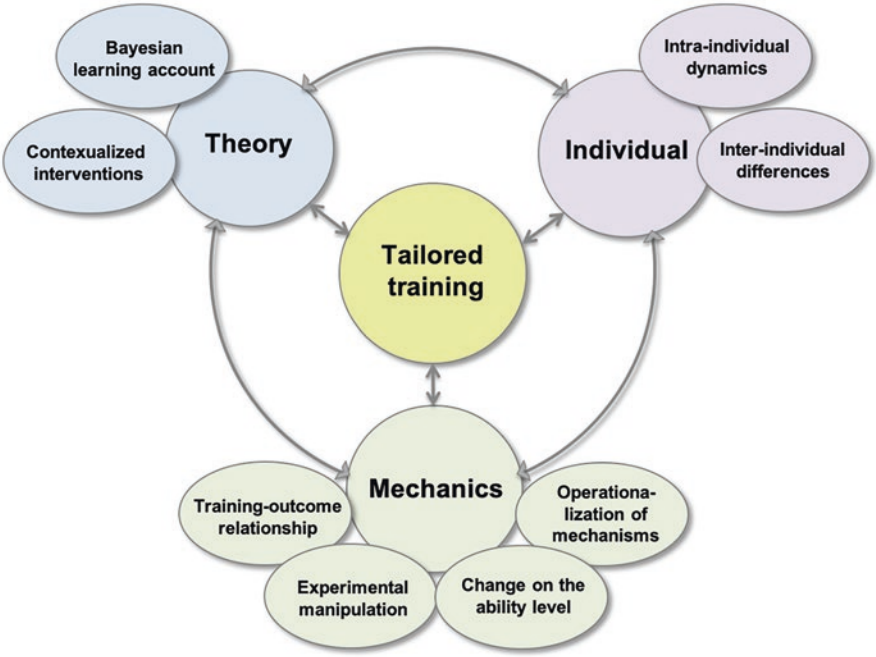

Fig. 1 Illustration of the framework for tailored cognitive training adapted from Smid et al. (2020). It is based on a process-based theoretical account considering the role of individual differences in the effects of interventions that draw on Bayesian models of development

mechanistic links between training mechanisms and transfer domains, (2) proposing theoretical perspectives detailing when and how a given training intervention can be most effective, and (3) acknowledging and analyzing individual differences in the effectiveness of training. We will briefly discuss the first two points in this section and the third one in Sect. 6.

First, a core assumption of cognitive training studies is that mechanisms of the trained ability are fundamentally related to the outcome measures of interest (for a review see Noack et al. 2009). Consider a classic example from the cognitive training literature: Working memory capacity correlates highly with general intelligence (Jaeggi et al. 2008). Thus, working memory capacity has been trained in order to increase intelligence. However, it has also been argued that two correlated variables, such as working memory span and fluid intelligence, do not necessarily co-vary when one is improved by training, because training can tap unshared variance between the two constructs (Moreau and Conway 2014). Moreover, even though working memory and fluid intelligence are correlated at a latent factor level, this is not necessarily true on the level of single tasks that are often used in training studies. Also, executive functions are higher-order processes that include different aspects. For instance, multitasking includes many abilities, such as task maintenance, scheduling, and selection, as well as the ability to disengage from one task and focus on another one. Thus, correlating two tasks is not sufficient to identify the underlying process-based nature of the relationship. Finally, considering task manipulations (e.g., increasing task-switching abilities) as equivalent to training for target variables may not be straightforward. For example, if it is not the task-switching ability per se that is related to the transfer measure but rather a shared executive attention-control mechanism, increasing switching abilities may not do much to improve performance on the transfer measure (Sala and Gobet 2017).

To address these shortcomings, Smid et al. (2020) emphasized that it is paramount to understand the true relationship between training mechanisms and outcome variables. Yet, this can be difficult for many reasons, among them the task impurity problem in the measurement of executive functions (Kane and Engle 2003; Miyake and Friedman 2012). Lately, much progress has been made using latent variable approaches (Könen and Auerswald 2021) and generative computational models that allow parsing task performance into multiple distinct processes as well as directionality between processes (Sutton and Barto 2018). Results of such analyses can inform the design of cognitive training studies by identifying which training mechanisms need to be targeted to improve specific outcome variables.

Moreover, to make sure that appropriate training mechanisms are identified and targeted, experimental manipulations, such as dual-task paradigms, may be more informative than correlations. In order to show change on the (latent) ability level, training should be applied across a range of tasks and not just single task manifestations (Noack et al. 2014). Finally, we need to consider how abilities can be improved rather than just task performance, that is, we need an appropriate operationalization of training mechanisms (e.g., cognitive, neural) that are being studied. For instance, executive function training often simply reduces the response time window, which might train the response speed but not necessarily the capacity itself.

Current theoretical accounts on far transfer are also missing detailed assumptions regarding how an intervention has to be designed and embedded in order to be effective. For instance, it has been suggested that interventions should be particularly effective in childhood (Wass et al. 2012), because cortical circuits specialize over development (*interactive specialisation hypothesis*, Johnson 2011).

Also, recent studies have used Bayesian learning accounts to study developmental plasticity (Stamps and Frankenhuis 2016). They assume that by using a probability distribution, Bayes‘ theorem provides a logically consistent way to model the individual assessment of current conditions in the external environment. These models assume that people have naive priors that are updated when they are continuously exposed to potentially informative cues over the course of their lives, resulting in a series of posterior distributions. Development evolves based on a child’s assessment of their current environmental conditions and is reflected by their posterior distributions. Smid et al. (2020) suggested that cognitive training can be seen as such cues that are assessed regarding their informativeness and reliability (i.e., the extent to which a specific cue is differentially associated with different environmental conditions). This framework predicts that interventions with poor reliability (regarding an individual’s actual experience of the environment) are likely to have limited to no impact, which is why context is likely of particular relevance. In fact, there is evidence suggesting that the context of the intervention may be of particular relevance. Isolated interventions focusing only on specific aspects of cognition without any embedding lead to limited transfer, while interventions that were contextualized in terms of how and where they were delivered proved to be more effective (Diamond and Lee 2011). Thus, Bayesian accounts of learning can be informative for the design and evaluation of interventions (Smid et al. 2020).

4 Task-Switching Training

A number of studies designed to improve multitasking have applied task-switching training. Some of them were designed to shed light on the cognitive mechanisms contributing to training-related performance gains (mechanistic studies), others aimed at showing causal effects of the intervention as compared to appropriate control conditions (efficacy studies; Green et al. 2019). In task-switching studies, participants are usually instructed to perform at least two simple tasks, A and B (see Fig. 2). Participants either perform each task in separate blocks (single-task blocks) or they have to switch between tasks (mixed-task blocks). The task switches can occur randomly and be announced by an external cue (cued switching paradigm) or they can follow a predictable task sequence (e.g., AABBAABB…). In predictable switching tasks, participants have to monitor the task sequence throughout the block in order to switch tasks at the appropriate time, but they also have the opportunity to prepare for upcoming task switches in advance. These types of switching designs allow to calculate two types of costs that represent different aspects of executive

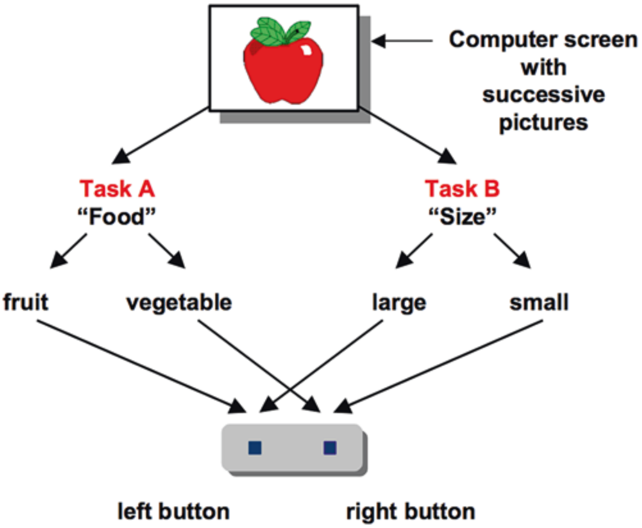

Fig. 2 Illustration of a switching task

functions: Mixing costs (also known as global or general switch costs) are defined as the difference in performance between single-task and mixed-task blocks[1] (this measure is conceptually comparable to dual-task costs, see below). They represent the ability to maintain multiple task sets in working memory and select the appropriate one. Switch costs are defined as the difference in performance between stay (AA, BB) and switch (AB, BA) trials in mixed-task blocks. They represent the ability to flexibly switch tasks on a trial-to trial basis in the context of interference from other active, competing task sets (see Koch et al. 2018 for a review).

4.1 Sources of Task-Switching Costs

There are different accounts explaining the source of task-switching costs. The stage-based perspective assumes that performing a task switch requires a task set reconfiguration in the form of a switch in the mental task set. This involves the activation and implementation of a new task set and reflects a switch-specific bottleneck process (e.g., Monsell et al. 2000; Rubinstein et al. 2001). This reconfiguration process costs resources that are reflected in the size of the switch costs. Many studies found that switch costs were reduced when the preparation time was increased (e.g., Karbach and Kray 2007; Kray and Lindenberger 2000; see Kiesel et al. 2010 for a review), indicating that the reconfiguration process can be initiated before the task is performed (Rogers and Monsell 1995). As a consequence, reaction times increase by less time than is needed for the reconfiguration process. However, even with sufficient preparation time, most studies report residual switch costs, pointing to persisting sources of interference and structural task limits. As a consequence, two-stage models of reconfiguration assume one stage representing cognitive flexibility (before stimulus presentation) and another one representing structural limitations for task readiness (triggered by stimulus presentation; see Koch et al. 2018 for a review).

However, aside from reconfiguration accounts, others have also assumed that switch costs arise more from a priming-based repetition benefit for stay trials compared to switch trials (e.g., Dreisbach et al. 2002; Sohn and Carlson 2000; Wylie and Allport 2000) or that they are due to cue encoding and retrieval benefits (Mayr and Kliegl 2003; Schneider and Logan 2005). Most important for the context of multitasking training, these accounts allow different predictions for transfer effects, not only from cued to predictable task-switching paradigms and vice versa (Minear and Shah 2008) but also from task switching to other tasks that require different levels of flexibility or inhibition, for instance. As a consequence, specific experimental

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[1] Computing mixing costs as the difference in performance between single-task and mixed-task blocks has the advantage that they are statistically independent (two orthogonal contrasts on the factor trial type), but the disadvantage that they are not theoretically independent. Therefore, some studies have computed them as the difference in performance between single-blocks and stay trials in mixed-blocks, which makes them theoretically independent, but not statistically.

manipulations in task-switching training studies may be a useful means to test theoretical accounts on the mechanisms underlying switch costs.

From a lifespan perspective, it is important to note that there are different developmental trajectories for the ability to flexibly switch between tasks (assessed via switch costs) and the ability to maintain and select task sets (assessed via mixing costs). While mixing costs follow an inverted u-shaped pattern from childhood to old age, lifespan changes in switch costs are less pronounced and often absent, especially when baseline differences in reaction times are taken into account (e.g., Kray and Lindenberger 2000; Kray et al. 2008; Karbach and Kray 2009; see Verhaeghen and Cerella 2002; Wasylyshyn et al. 2011 for meta-analyses). Thus, many task-switching training studies aimed at compensating these age-related performance impairments and investigating lifespan changes in cognitive plasticity.

Studies assessing task-switching training usually applied pretest-training-posttest designs with one or more treatment groups that practiced switching between tasks in random or predictable task orders. Active control groups often performed the same tasks but practiced them in separate blocks (i.e., single-task blocks) (see Minear and Shah 2008, who introduced this type of design; see also Sect. 2.2).

4.2 Task-Switching Training Gains

Most of these studies demonstrated robust and substantial training-related improvements in task-switching performance across various age groups, from children and adolescents (for a review, see Karbach and Kray 2021) to younger and older adults (for meta-analyses, see Karbach and Verhaeghen 2014; Nguyen et al. 2019) and also clinical groups, such as children with attention-deficit hyperactivity disoder (ADHD) (e.g., Dörrenbächer and Kray 2019; Kray et al. 2012). For instance, Karbach and Kray (2009) showed that the costs of switching between tasks were significantly reduced after just four sessions of practice. Training net gains ranged from 0.85 SD to 1.88 SD across training conditions, and a variable training (on a new set of stimuli and task rules in each training session) showed the smallest training gains (cf. Sabah et al. 2019).

In a meta-analysis, Karbach and Verhaeghen (2014) found training improvements in task switching in older adults, with raw gains of about 0.90 SD and net gains (after subtracting the effects of active controls) of about 0.50 SD. Though nearly all studies report a reduction of switch costs on the level of latencies, it should be noted that the findings on the reduction of switch costs on the level of accuracy were mixed, probably because these costs are usually already relatively low at the beginning of the training, at least in healthy adults.

4.3 Near Transfer Gains

Consistent with the practice effects of training in task switching, most studies also reported near transfer effects to untrained switching tasks across various age groups (e.g., Minear and Shah 2008). For instance, Minear (2004) reported a series of five experiments focusing on the transfer of task-switching training. Participants either completed a two-day task-switching training on mixed-task blocks or a control condition that only included single-task blocks. The first two experiments showed a reduction in mixing costs and switch costs after training. However, only the improvement in mixing costs transferred to a new, untrained switching task. This finding was consistent across a random as well as a predictable switching paradigm. In three further experiments, Minear investigated whether the effects of training are specific to the context of a particular paradigm, that is, whether training by means of a predictable paradigm transfers to a random paradigm and vice versa. Results replicated the findings from the first two experiments by showing transfer on the level of mixing costs within one paradigm, but no evidence for transfer from one training regimen to another, indicating that the transfer benefits seemed to be limited to the trained paradigm. Minear argued that participants in both paradigms improved during training due to strategic shifts in goal selection; however, this change may have been associated with different trial-type expectancies after practice in the random group, while the performance improvements in the predictable paradigm may be due to improved task preparation. In terms of transfer effects, Minear and Shah (2008) assumed that the most likely sources of transferable gains were training effects in the ability to resolve task-set conflicts (Kray and Lindenberger 2000; Mayr 2003; Mishra and Gazzaley 2014). Given that task-set competition is particularly large after a switch, successfully resolving this competition may be accomplished by increased attentional control (Hübner et al. 2001).

In line with the theoretical view that a considerable supply-demand mismatch is a precondition for inducing plasticity in cognitive performance (Lövdén et al. 2010), the amount of near transfer varied with age when training conditions were the same across age groups. For instance, Minear et al. (2002), examined age differences between younger and older adults in the transfer of task-switching training – compared to the training of the two single tasks – to a similar switching task by means of a predictable switching paradigm. Both younger and older adults showed a substantial reduction in mixing costs after two days of training. In contrast to the training of the two single tasks, task-switching training resulted in the transfer of these training gains (i.e., a reduction of mixing costs) to a nontrained similar switching task. This transfer effect was more pronounced for older adults than for younger adults. Consistently, near-transfer gains were much larger in healthy children and older adults than in younger adults in the task-switching training study from Karbach and Kray (2009). Since the training in both studies was not adaptive, it may have induced a larger demand-supply mismatch in children and older adults that typically show age-related alterations in brain regions associated with task switching. Moreover, the meta-analysis of Karbach and Verhaeghen (2014) showed clear near-transfer gains of executive function training in older adults with raw gains of about 0.47 SD and net gains (after subtracting the effects of active controls and adjusting for publication bias) of about 0.30 SD.

There is also evidence indicating that for younger adults and adolescents, near-transfer gains can be restricted to the general level of task switching (mixing costs) or to a predictable switching training (Pereg et al. 2013; Zinke et al. 2012), which may have induced a larger mismatch between task demands and brain supply. This is in line with results from a study by Kray and Fehér (2017). In their training, demands on switching (single-task vs. mixed-task blocks), interference control (unambiguous or ambiguous stimuli), and working-memory demands (with or without task cues) varied between different training conditions. Interestingly, transfer gains in younger adults did not vary across these conditions. In contrast, older participants that trained on tasks with high levels of task interference (ambiguous groups) showed larger transfer gains than participants trained on unambiguous stimuli inducing less task interference. Again, this supports the idea that training of top-down executive control networks required for resolving task interference in multitasking situations is a promising training approach to induce transfer, especially in groups that show major deficits in these abilities (cf. Mishra and Gazzaley 2014).

4.4 Far Transfer Gains

Finally – and in line with the outcomes of other types of training - results on far transfer effects of training in task switching are rather mixed. Some studies found a relatively broad transfer to other executive functions and even to measures of fluid intelligence, including inhibition, working memory, and fluid intelligence in healthy individuals across the lifespan (e.g., Karbach and Kray 2009) and to inhibition and working memory in children with ADHD (Kray et al. 2012). A recent study investigating normally developing children (8–11 years of age) provided similar results: Multitasking training in this study included task-switching, focus-switching, and dual-task training (Johann and Karbach 2020). Aside from near transfer to untrained multitasking paradigms, a game-based version of the training resulted in far transfer to reading ability (while a standard version did not) that was still present in follow-up after three months. However, other studies found no far transfer effects at all after task-switching training in adolescents (Zinke et al. 2012), younger adults (Pereg et al. 2013), and older adults (Kray and Fehér 2017). For instance, both Pereg et al. (2013) and Zinke et al. (2012) investigated transfer of predictable task-switching training to inhibition, working memory, and response speed, while Kray and Fehér (2017) focused on transfer to working memory, inhibition, and fluid intelligence.

Studies focusing on very young children (Kindergarten and preschool age) usually do not apply the classic task-switching paradigm, but child-friendly versions, such as the Dimensional Change Card Sort task (DCCS). Kloo and Perner (2003), for instance, investigated the development of switching ability and theory of mind in 3- to 4-year-olds by means of the DCCS and the false-belief task. They found that DCCS training improved performance on the false-belief task and vice versa, suggesting a close developmental link between switching abilities and theory of mind. Similarly, Fisher and Happé (2005) trained autistic children (6–15 years of age) either in theory of mind tasks or a DCCS-like task. Participants were tested before training, after training, and at a 2-month follow-up. Results showed performance improvements in theory of mind tasks after both types of training that were still present at follow-up.

The mixed pattern of findings regarding far transfer of task-switching training is also reflected in the results of recent meta-analyses. They suggest that far transfer of training to other executive functions and fluid intelligence is small but significant (net gain of about 0.20 SD), especially in older adults (Karbach and Verhaeghen 2014; Nguyen et al. 2019), supporting the pattern of compensation effects reported in previous studies (see below).

In sum, previous studies indicate that task-switching training resulted in substantial training gains and near transfer effects as well as small but significant far transfer effects, especially in clinical samples and older adults. However, transfer seems to be less pronounced in adolescents and young adults.

5 Dual-Task Training

The discussion of dual-task training is mainly focused on studies with simultaneous component tasks, demonstrating that dual-task performance is optimized as a result of extended training. In particular, these studies allow to pinpoint the learning mechanisms underlying this optimization (e.g., Ahissar et al. 2001; Liepelt et al. 2011a, b; Oberauer and Kliegl 2004; Ruthruff et al. 2001; Ruthruff et al. 2006; Strobach et al. 2008; Van Selst et al. 1999) and are thus mechanistic studies (Green et al. 2019). In such training studies, dual-task costs were relatively high at the beginning of training. However, after extended training, these costs were (nearly) eliminated, suggesting an enormous optimization of dual-task processing and demonstrating a training effect. The aim of the present section is to review mechanisms explaining eliminated costs by analyzing near and far transfer effects, i.e., we will apply the analysis of transfer effects as a tool to learn about training-related mechanisms. We will, therefore, (1) summarize sources that impair dual-task performance at low levels of training (i.e., sources of dual-task costs before training starts) and (2) refer to mechanisms that reduce the impact of these sources with training by the analysis of transfer effects after training. Finally, we review the impact of age on these mechanisms.

5.1 Sources of Dual-Task Costs

5.1.1 Sources of Dual-Task Costs within the Component Tasks

Dual-task situations of the psychological refractory period (PRP) type are one of the most prominent paradigms to precisely investigate processes that are sources of dual-task costs and are located within simple component tasks (Pashler 1984, 1994a; Pashler and Johnston 1989, 1998; Schubert 1999; Schubert et al. 2008; Telford 1931; Welford 1952). As illustrated in Fig. 3a, these component tasks are typically speeded sensorimotor tasks (e.g., auditory tasks, where tone pitch is mapped on vocal responses, and visual tasks, where stimulus location is mapped on manual finger responses) that can be divided into three processing stages (in this order): perception stage, response selection stage, and motor stage. To explain the PRP effect in PRP situations, the *central bottleneck theory* (Fig. 3b) holds that the selection of which response to execute cannot be made for two tasks in parallel. Instead, this model assumes sequential response selection of Tasks 1 and 2 in a dual-task situation due to a structural and unavoidable processing bottleneck (Pashler 1994a). Next to a central bottleneck stage, there are also assumptions about peripheral bottlenecks such as a bottleneck at the final motor stage (e.g., Bratzke et al. 2009). Optimizations in these bottleneck stages might mark one mechanism explaining improved dual-task performance after training.

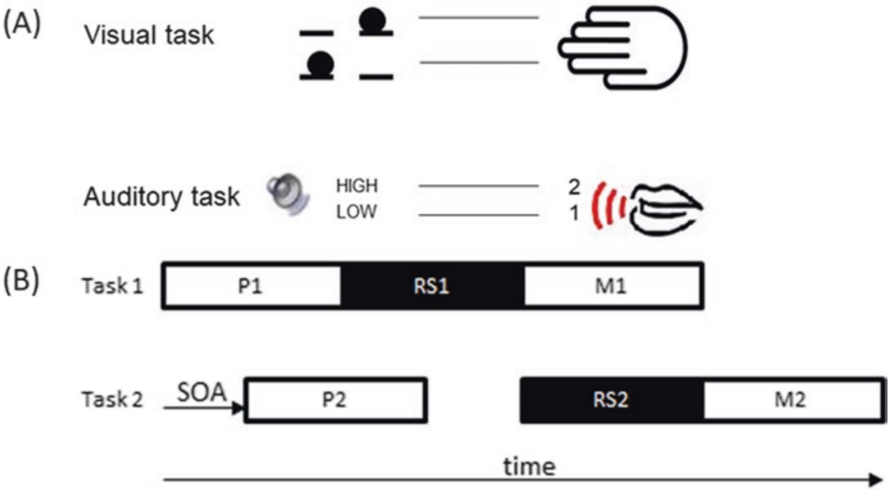

Fig. 3 (**a**) Illustration of a typical visual and auditory speeded sensorimotor task. (**b**) Dual-task processing architecture according to the central bottleneck theory in dual tasks of the psychological refractory period (PRP) type with stimulus onset asynchrony (SOA) manipulations. Central response-selection (RS1; RS2) stages in Task 1 and Task 2 are processed sequentially, while perception (P1; P2) and motor response (M1; M2) stages are processed in parallel

5.1.2 Sources of Dual-Task Costs Outside the Component Tasks

Alternative to the central bottleneck theory, *resource theories* assume that two response selections can be processed in parallel in dual tasks, but sharing the same limited attentional resource(s) causes dual-task costs (e.g., Pashler 1994b; Tombu and Jolicoeur 2003; Wickens 2008). Consistent with this view, participants were shown to strategically prioritize one task over another following instructions, demonstrating flexible allocation of limited attentional resources (e.g., Gopher et al. 1982; Navon and Gopher 1979; Norman and Bobrow 1975). Thus, optimization in dual-task attention allocation may represent a mechanism of training-related reductions of dual-task costs. That is, this mechanism could explain that scheduling of limited attentional resources as a source of the difficulty to perform two simultaneous tasks is overcome with training.

Recent studies applied adaptations of the PRP paradigm with varying task orders for analyses of executive control functions (Jiang et al. 2004; Kamienkowski et al. 2011; Liepelt et al. 2011b). Such executive functions, among others, coordinate the processing of two task streams of a dual task (e.g., De Jong 1995; Luria and Meiran 2003; Schubert and Szameitat 2003; Sigman and Dehaene 2006; Szameitat et al. 2006). From a perspective of executive processes, dual-task performance data may thus point to a set of task coordination processes (Kübler et al. 2019; Strobach et al. 2019) that improve with training.

5.2 Analysis of Transfer Effects to Investigate Training Mechanisms

5.2.1 Transfer Effects and Mechanisms Within the Component Tasks

The dual-task training literature investigates the impact of skills for optimized component task processing on improved dual-task performance by analyzing transfer effects mainly in the following way: Which specific processing stages within simple component tasks are optimized and thus shortened as a result of dual-task training – the initial stimulus perception stage, the central response selection stage, the final motor response stage, or a combination of these stages (Pashler and Baylis 1991)?

Some training studies have already addressed the question of the locus of training effects within dual tasks of the PRP type (e.g., Ahissar et al. 2001; Anderson et al. 2005; Dux et al. 2009; Garner et al. 2014; Kamienkowski et al. 2011; Ruthruff et al. 2001, 2006; Sangals et al. 2007; Strobach et al. 2013; Van Selst et al. 1999). First, studies aiming to precisely locate stage shortening in component tasks made use of the phenomenon of the backward compatibility effect. This effect is demonstrated by RT1 that is shorter when Task 2 requires a compatible versus an incompatible response to the response in Task 1 (e.g., say “left” and press the left key vs. say “left” and press the right key; e.g., Ellenbogen and Meiran 2008; Hommel 1998; Hommel and Eglau 2002; Watter and Logan 2006). This phenomenon may be due to an overlap and parallel processing of some portions of stimulus-response mappings at the central stages in both tasks (e.g., Hommel 1998; Janczyk et al. 2014). In a training study, Thomson et al. (2015) showed that the size of the backward compatibility effect is closely associated with the duration of the response selection stage in Task 1. When this stage was shortened through PRP training, the magnitude of the effect decreased. In turn, when the duration of Task 1 response selection was increased after the end of training by increasing the number of stimulus response mapping rules in a near transfer situation, the backward compatibility effect increased by a magnitude similar to this increased duration. These transfer findings are consistent with the assumption that the response selection stage is shortened with training, and this shortening might contribute to the training-related reduction of dual-task costs.

Furthermore, Strobach et al. (2013) applied a near transfer logic originally proposed by Pashler and Baylis (1991). To identify the particular processing stages which potentially undergo a training-related shortening at the end of eight training sessions (cf. Klingberg 2010), the authors introduced transfer manipulations separately targeting processing routines at the perception, the response selection, and the motor stages. As a consequence, the processing routine may or may not be applied in the transfer situation. According to this transfer logic, the transfer manipulation was supposed to lead to an increase in processing time if participants cannot use a processing routine any longer than was sped up due to learning (illustrating no transfer). On the other hand, no increase in processing time is expected if learning has not led to a speed-up of a processing routine (illustrating transfer).

Consistent across a visual and an auditory task (e.g., Schumacher et al. 2001), changing the mapping rules from the end of training to a transfer test resulted in a significant RT increase from the former to the latter conditions. This result suggested no transfer of the trained mappings, and it was conclusive evidence for response-selection stage shortening. Consistent with the applied transfer logic, stimulus information processing and response processing were also manipulated separately. However, none of these latter manipulations resulted in strong RT prolongations. Thus, there is no evidence for transfer of mapping rules after dual-task training, which is consistent with the assumption of central stage shortening to explain improved dual-tasking after training. However, there is no evidence for perceptual and motor stage shortening during training.

5.2.2 Transfer Effects and Mechanisms Outside the Component Tasks

After reviewing the impact of transfer on the investigation of mechanisms within component tasks, we will review a second set of mechanisms underlying the reduction of dual-task costs. This set of mechanisms is located outside the component tasks and is related to the optimization of attention and executive functions (Damos and Wickens 1980; Hirst et al. 1980; Kramer et al. 1995).

Optimized attention allocation proposes the acquisition of skills for an efficient strategic allocation of limited processing resources to optimally process two simultaneous tasks. Most importantly, we assume that such skills are acquired during training in which participants are instructed to flexibly vary their attentional resources between the two tasks by constantly varying their task response priorities (this training type is referred to as the variable-priority condition; e.g., Kramer et al. 1995). These skills should be independent of the trained tasks and should be transferable to near transfer situations at least. In contrast to a variable-priority condition, participants are instructed to emphasize both tasks constantly and equally in a fixed-priority condition. Under this condition, there should be no variation of attentional resources during training and therefore no acquisition of transferable skills for optimized attention allocation. In a series of studies, dual-task improvement was analyzed as an effect of four to six training sessions under the variable-priority and fixed-priority conditions to test the acquisition of optimized attention allocation skills (Bier et al. 2014; Gagnon and Belleville 2012; Lee et al. 2012; Voss et al. 2012; see also Bherer et al. 2005, 2006, 2008; Kramer et al. 1995, 1999). In fact, at the end of the training, the assessment of dual-task performance with the trained dual tasks as well as with nontrained transfer dual tasks indicated a larger training-related reduction of dual-task costs under the variable-priority condition in contrast to the reduction under the fixed-priority condition (training and transfer effects, respectively). These findings are consistent with the assumption that with variable-priority training, there is an acquisition of skills for an efficient allocation of limited attentional resources to the processing of two simultaneous tasks, contributing to the reduction of dual-task costs with training. These skills are not specific for the trained task characteristics but are transferable to new tasks.

So far, training studies allowed no investigation of well-identifiable executive processes and thus a direct test of the acquisition of task coordination skills (Damos and Wickens 1980; Kramer et al. 1995; Oberauer and Kliegl 2004), because these studies do not compare the performance after single-task and fixed-priority training in the trained situation and transfer situations. Such a comparison was conducted in Liepelt et al. (2011b) and Strobach et al. (2012a). In these studies, the authors compared the dual-task performance of two groups of participants experiencing different types of training with a visual and auditory task for seven sessions (e.g., Schumacher et al. 2001). While (1) fixed-priority dual-task training included intermixed presentation of both tasks in dual tasks and in single tasks, in dual-task blocks and separate presentation of both tasks in single-task blocks, respectively (see also Hazeltine et al. 2002; Schumacher et al. 2001), (2) pure single-task training included the exclusive presentation of the visual and auditory tasks in separate single-task blocks. In fact, after dual-task training, dual-task performance was improved when compared to the performance after single-task training. In detail, this improvement was exclusively demonstrated by reduced dual-task RTs in the auditory task, while there was no such dual-task evidence in the visual task. The auditory task and the visual task are typically performed slower and faster, respectively, indicated by longer and shorter RTs in single and dual tasks (see also Hartley et al. 2011; Schumacher et al. 2001; Strobach et al. 2008, Strobach et al. 2012b, c; Tombu and Jolicoeur 2004).

As proposed by the Efficient Task Instantiation (ETI) Model (Schubert and Strobach 2018; Strobach et al. 2014), one specific realization of the optimized task coordination explaining the dual-task-training advantage in the longer auditory task might be as follows: The dual-task processing architecture includes (1) a within-task capacity limitation (i.e., bottleneck process) in the faster visual task (e.g., at a central response selection stage), followed by (2) a switching operation, and (3) the within-task capacity limitation in the slower auditory task (Band and van Nes 2006; Lien et al. 2003; Stelzel et al. 2009). The switching operation is theorized as activating and/or instantiating the rules that map Task 2 stimuli onto responses (Maquestiaux et al. 2004). It may be that the rules must be moved back into working memory or that the rules remain in working memory throughout the task. After dual-task training (Fig. 4a) in contrast to single-task training (Fig. 4b), activation/instantiation processes are highly efficient due to task coordination skills, leading to a shortening of the switching operation: Participants might have learned to load task information faster or more information at a time into the working memory component. Since the location of this shortened switching operation after the response selection stage in the faster visual task and before this stage in the slower auditory task improved, dual-task performance occurs in this latter task exclusively.

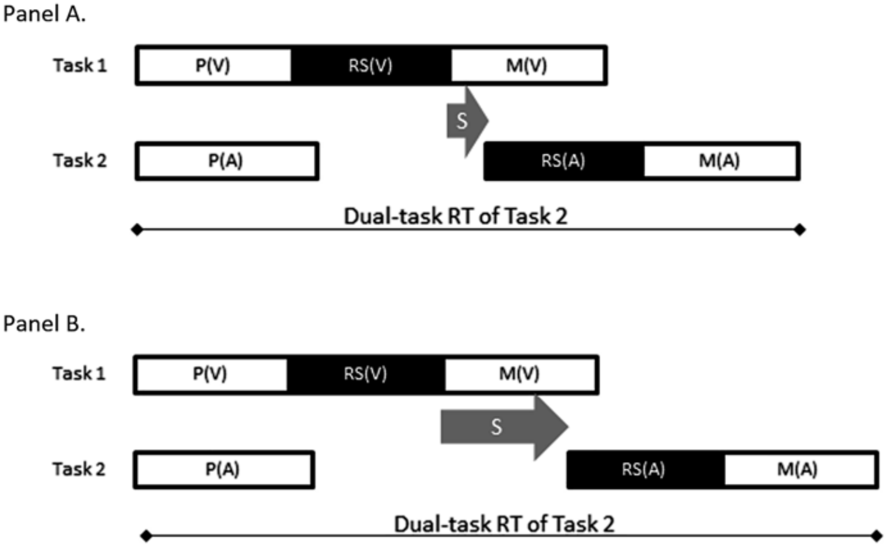

Fig. 4 Illustration of the hypothetical time relation of processing stages in Task 1 (e.g. a Visual task) and Task 2 (e.g., an Auditory tasks) as shorter and longer task, respectively, when presented in a dual-task situation with SOA = 0 ms. P(V), and P(A) indicate the perception stages; RS(V) and RS(A) indicate the central response-selection stages (including bottleneck characteristics); M(V) and M(A) indicate the motor stages; S indicates switching between component tasks after the completion of RS(V) and before the start of RS(A). Panel (**a**): Hypothetical time relation of dual-task processing at the end of dual-task training including a short switch (i.e., optimized instantiation of information of two tasks) after the completion of RS(V) and before RS(A), leading to relatively short dual-task RTs in the auditory task. Panel (**b**): Hypothetical time relation of dual-task processing at the end of single-task practice including no optimized switch after the completion of RS(V) and before RS(A), leading to relatively long dual-task RTs in the auditory task

One important aspect is that the dual-task improvement after dual-task training was evident not only in trained dual tasks but also in (near) dual-task transfer situations that introduced changes in specific properties of either the visual or the auditory task (Liepelt et al. 2011b; Schubert et al. 2017). These findings provide first evidence that acquired task coordination skills are not tied to specific properties of the trained component tasks but are transferable to different dual-task situations. This means that these findings preliminarily support the assumption of the near transferability of acquired task coordination skills.

In addition to exclusive lab-based studies, there also exist a number of studies testing the acquisition and transferability of task coordination skills with real-world dual-task training; these tasks are supposed to provide a natural variability during dual-task training. For instance, the case of persons with experience in simultaneous interpreting in contrast to persons with consecutive interpreting experience might represent a contrast between persons with dual-task training with a natural variability (e.g., simultaneous listening and speaking) and persons without such training, respectively (Becker et al. 2016; Strobach, Becker et al. 2015). In fact, RTs in Task 1 and Task 2 of a PRP dual task were reduced in simultaneous interpreters in contrast to consecutive interpreters. So, data of the PRP dual-task situation is consistent with the assumption of transferable task coordination skills.

Similar conclusions can be drawn from investigations of persons with extensive experience in playing video games. In fact, when persons are trained in action video games (requiring multiple simultaneous tasks and actions which classify as dual-tasking) for 15 hours and are tested in a PRP dual task, their RTs are reduced in contrast to RTs of persons with no such experience (Strobach et al. 2012d; see also Chiappe et al. 2013). Again, PRP component tasks are not related to the context of experience (i.e., the video games). Hence, action video gamers might have optimized task coordination skills that were acquired from a variable real-world task and were demonstrated in a lab-based situation with simple component tasks. This set of conclusions is consistent with the assumption of transferable task coordination skills (Strobach 2020). To sum up, the present section showed that there is substantial evidence for optimized attention allocation, as well as some evidence for optimized task coordination.

5.3 Dual-Task Training Mechanisms and Aging

Some of the studies focusing on mechanisms underlying training effects investigated these effects from a cognitive aging perspective, not only in younger adults but also in older adults. Basically, these studies focused on mechanisms located outside the component tasks, related to skills for improved attention allocation as well as task coordination. In fact, dual-task improvement after training under the variable-priority conditions in comparison to this improvement under fixed-priority conditions to test the acquisition of optimized attention allocation skills indicated a larger training-related reduction of dual-task costs in the trained dual tasks as well as in nontrained transfer dual tasks in older adults (Bier et al. 2014; Gagnon and Belleville 2012; Lee et al. 2012; Voss et al. 2012; see also Bherer et al. 2005, 2006, 2008; Kramer et al. 1995, 1999). These findings are consistent with the assumption of an acquisition of transferable skills for an efficient allocation of limited attentional resources to the processing of two simultaneous tasks. Importantly, this acquisition is to some extent age-independent.

This age independency was also investigated with a focus on the acquisition of task coordination skills. To do so, the training and transfer effects of single-task and fixed-priority training were tested in the trained situations and in near transfer situations (Strobach, Frensch et al. 2015) as well as in far transfer situations (Anguera et al. 2013) after 7 and 12 sessions of training, respectively. In all of these situations, performance was improved after the latter type of training. This indicates that similar to skills for an efficient allocation of attention recourses, improved task coordination skills can be acquired, they are independent, and, most importantly, here, they are independent of age across adulthood. Thus, mechanisms explaining improved dual-task performance can be generalized from younger to older adults.

In sum, there is ample evidence indicating that dual-task training results in robust performance improvements on the trained task as well as significant transfer to untrained dual-task situations. These training gains are based on optimized attention allocation processes and optimized task coordination and are stable across the adult lifespan. After reviewing previous evidence on the effects of multitasking training (task-switching training, dual-task training) and discussing the underlying mechanisms, we will highlight an issue that has been increasingly acknowledged in the field of multitasking training by discussing the importance of analyzing individual differences in training outcomes.

6 Integrating Effects of Task-Switching and Dual-Task Training

The previous sections have shown that there is substantial evidence for the effects of multitasking training by means of task-switching and dual-task training, but unfortunately, these findings never seem to have been integrated. However, shedding light on what findings are common across paradigms and identifying critical differences may help understand the underlying mechanisms. To do so, it may be helpful to examine studies that assessed the effects of training in one of those areas (e.g., dual-tasking) and analyze the transfer effects in the respective area (e.g., task-switching). The occurrence of transfer would indicate that there is a conceptual connection between both aspects of multitasking; a lack of transfer would suggest that there may not be such a connection. Unfortunately – and also a bit surprisingly – only a few studies have examined transfer between the two paradigms, and both are from the area of dual-task training (Strobach et al. 2012a, d). There is a third study (Johann and Karbach 2020), but given that participants trained both task switching and dual tasking, it does not allow clear conclusions regarding the transfer of dual-task training to task switching. In Strobach et al. (2012a), participants trained relatively homogeneous (i.e., uniform) dual tasks (Hazeltine et al. 2002; Schumacher et al. 2001), and compared to single-task training, there was no transfer to a predictable task-switching paradigm. However, when training was more variable (in the form of an action video game, Strobach et al. 2012d), it benefitted performance on dual tasks of PRP type (reduced PRP effect) and task switching (reduced switching costs, but not mixing costs) compared to Tetris training (more consistent with single-task training). These transfer effects from dual-task training to task switching thus are consistent with the assumption of a conceptual connection between both types of multitasking situations and suggest that some components are common to dual tasks and task switching. It is also consistent with a previous study reporting fairly substantial correlations between switch costs and PRP effects within subjects (Hirsch et al. 2019).

Even though this is not much evidence to go on, these results indicate that examining the pattern of training and transfer effects across different multitasking paradigms more closely and systematically may tell us more about the specific executive control processes involved in multitasking. The existing findings, however, suggest that the PRP effect may in fact be related to shifting processes. Together with the substantial correlations that Hirsch et al. (2019) also reported between dual-task costs and mixing costs, it seems likely that performance costs in multitasking may not measure the underlying executive control processes as isolated and differentiated as it has been assumed in the past – a fact that has been acknowledged widely and discussed in the context of the task impurity problem (Miyake et al. 2000). Moreover, considering the extremely low reliabilities of difference scores in multitasking paradigms (e.g., Draheim et al. 2019) and the resulting issues for the interpretation of correlations between these difference scores and other variables (Miller and Ulrich 2013), relying on other measures than performance costs may yield more reliable estimates of the conceptual overlap and the connections between different aspects of multitasking.

7 Individual Differences in Training Outcomes

The studies reviewed above showed that multitasking training can have positive effects on cognitive functions on the group level, especially in terms of training gains and near transfer effects, while evidence for far transfer remains mixed. However, previous studies consistently show that individuals respond differently to the same training intervention. This is particularly critical in children and older adults, as they are likely to differ more from each other than young adults, and between-group comparisons do little justice to individuals' strengths and weaknesses. Yet, these individual differences are often overlooked and most current approaches simply take univariate statistical approaches (e.g., ANOVA) that are unable to identify individual cognitive profiles of performance and training-induced benefits. Contemporary multivariate analysis methods (e.g., latent change modeling, machine learning) that are based on rich multivariate data offer promising new ways to analyze training data and associated transfer effects (e.g., Astle et al. 2018) by studying training-related changes in task relationships.

These approaches may help to answer the question who benefits most from cognitive interventions. This is obviously important from an applied point of view, especially when it comes to the adaptation of training interventions to populations with specific needs, such as children with neurocognitive disorders or older adults with specific cognitive impairments. Moreover, it is also of interest on the theoretical level, because individual differences in training-related benefits may help us understand the underpinnings of cognitive and neural plasticity. Also, the mismatch between environmental demands and brain supply that is induced may strongly vary between age groups or between healthy subjects and those with cognitive impairments and therefore needs to be considered in order to create optimal training interventions.

7.1 Interindividual Differences in Cognitive Performance at Baseline

In the past, two prominent accounts have been used to describe and explain interindividual differences in training-related performance gains: On the one hand, the magnification account (also Matthew effect or scissor effect) assumes that individuals that are already performing very well before they enter an intervention will also benefit most. It is assumed that high-performing and well-educated participants have more efficient cognitive resources to acquire and implement new strategies and abilities. Thus, we would expect a positive correlation between baseline cognitive performance at pretest and training-related gains as well as a magnification of age differences and interindividual differences after the training (see Fig. 5, left panel).

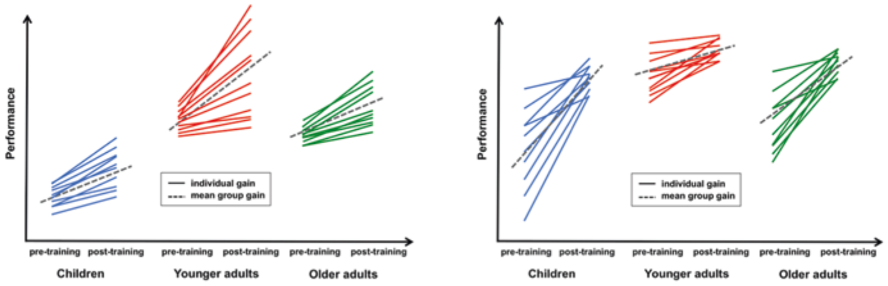

Fig. 5 Illustration of magnification (left panel) and compensation (right panel) effects after task-switching training: changes in interindividual differences in performance from pretraining to post-training, changes of age-group differences from pretraining to posttraining, and correlation between baseline cognitive performance at pretest and training gain. (Karbach and Kray 2021)

In fact, there are a number of earlier studies supporting this account, most of them from the field of strategy-based training, mostly from the domain of memory training (see Rebok et al. 2007, for a meta-analysis).

On the other hand, the compensation account assumes that high-performing individuals will benefit less from cognitive interventions, because they are already functioning at the optimal level and have less room for improvement. As a consequence, we would expect a negative correlation between baseline cognitive performance and training gains as well as a reduction of age differences and individual differences after the intervention (see Fig. 5, right panel). Evidence supporting this account mostly comes from process-based training studies, including task-switching training studies, revealing that training-related benefits were larger in children and older adults than in younger adults (for a review, see Karbach and Unger 2014). While these studies were based on comparisons at the group level, recent studies also analyzed correlations between baseline cognitive ability and training-related benefits, indicating that executive function training yielded larger training and transfer effects in older adults with low cognitive performance at pretest (e.g., Zinke et al. 2014). Moreover, recent studies have started applying latent variable approaches to analyze individual differences in performance changes and correlations between baseline cognitive ability and training-related benefits (see also Könen and Auerswald 2021; Könen and Karbach 2021). This research also provided evidence for the magnification effects after memory-strategy training and compensation effects after task-switching training (cf. Könen and Karbach 2015).

For example, a recent study including children, younger adults, and older adults directly tested the magnification account against the compensation account in a lifespan sample that had performed task-switching training (Karbach et al. 2017). The authors applied latent-change modeling and tested changes in individual differences and age differences from baseline to posttest as well as the correlation between baseline cognitive abilities and training as well as transfer gains. Results showed a reduction of both individual differences and age differences after the training and indicated that lower baseline abilities were associated with larger training-induced gains. Importantly, this correlation was significantly higher in the training group than in the active control group, indicating that this pattern was more likely based on the effects of executive control training than on nonfocal effects (e.g., regression to the mean or retest effects).

When it comes to dual-task training, the evidence is less clear because of the lack of studies on this issue. To our knowledge, there is only one study that tested individual differences in training gains in younger and older adults (Strobach, Gerstorf et al. 2015). The authors applied the performance variability (i.e., variability in RTs) as a proxy for inefficient neural processing in the beginning of training and assessed whether this variability can predict the amount of improvement with later training in dual-task performance. In both age groups, the speed of dual-task processing increased with practice, and variability associated with the means was reduced. Most importantly, variability allowed predicting dual-task training benefits in both age groups, showing that baseline dual-task costs at the beginning of training were both positively and negatively related to training gains. These relations also varied as a function of age group and component tasks, indicating that both magnification as well as compensation effects were present after dual-task training.

7.2 Interindividual Differences in Noncognitive Variables at Baseline

Training-induced gains also vary as a function of noncognitive factors, such as individual differences in motivation, personality, genetic predisposition, etc. (Strobach and Karbach 2021). Motivational aspects have lately been discussed as important predictors for training gains (see Johann and Karbach 2020; Katz et al. 2021). Locke and Braver (2010) assumed that motivation aligns goal-directed behavior by modulating the effort individuals are willing to invest to achieve goals. It thus seems likely that training willingness and possibly training gains are affected by motivational factors. In order to increase motivation and training willingness, game elements have been added to the tasks in many training regimes. Surprisingly, very few studies have systematically compared game-based training tasks to standard training tasks.

Prins et al. (2011) examined the benefits of adding game elements to EF training in children with ADHD (7–12 years of age). The game-based training enhanced motivation (assessed by the time voluntarily spend on training), training performance, and transfer to an untrained EF task as compared to the standard training setting. Dörrenbächer et al. (2014) investigated the effects of a task-switching training in a high-motivational setting (with game elements) and a low-motivational setting (without game elements) in middle-aged children (8–11 years of age). They found that training willingness and near transfer in switching costs – but not far transfer – was enhanced in the high-motivational setting as compared to the low-motivational setting. Johann and Karbach (2020) relied on the concept of intrinsic interest and the self-determination theory (SDT; Ryan and Deci 2000) to develop working memory training, an inhibition training, and a multitasking training in a game-based and a standard version, respectively. The game-based versions featured experimental manipulations designed to satisfy three basic psychological needs: relatedness (feeling connected and involved with others and having a sense of belonging), autonomy (need to experience one's behavior as self-determined), and competency (feeling effective in one's interactions with the environment). SDT assumes that fulfilling these needs increases intrinsic motivation, which may enhance training motivation and training-induced performance gains. In the game-based version, a cover story framing the tasks served to enhance the feeling of relatedness (see Fig. 6a–d. In each task, participants had the opportunity to earn magic power points improving the strength of the protagonist to enhance the feeling of perceived competence (see Fig. 6e). In order to increase the feeling of autonomy, there were pseudo-choices providing participants the opportunity to decide which route to take. All training tasks were adaptive (i.e., task difficulty was continuously

Good, you earned 2 magic power points
Overall, you have 2 magic power points

Fig. 6 Exemplary pictures from the cover story and the training tasks in Johann and Karbach (2020). The map of the kingdom Asfallon (**a**); where the king and the queen ruled until the evil wizard Ansgar destroys the magic stone and takes the control of the kingdom (**b**); the protagonists Edvin, Bragi, and Finja (**c**); Edvin fighting against Ansgar at the end of the story (**d**); feedback in terms of magic power points in the game-based setting (**e**); example for an inhibition training task (**f**). (Schaeffner et al. 2021)

adapted to individual performance across 7 levels), and a progress bar changed color after responses that were correct and provided fast enough (see Fig. 6f) or after responses that were incorrect or too slow. Results showed that adding the game elements did not modulate training effects, but there were differences between performances in the game-based and the standard version regarding far transfer to academic abilities: performance improvements on a reading measure were larger in the game-based inhibition and game-based multitasking training group as compared to the control group. Those transfer effects were not found in the standard inhibition or standard multitasking training group. This result is in line with previous evidence that isolated training of specific cognitive functions, such as executive functions in a narrow task context, may constrain transfer to dissimilar activities in complex activity contexts (Greeno et al. 1993; Schwaighofer et al. 2015). According to this view, adding game elements to executive control training tasks may enhance the complexity of the training context and thus facilitate transfer to academic abilities that are also acquired and practiced in a complex context.

Since executive functions are associated with personality factors (e.g., Neuenschwander et al. 2013), it also seems likely that personality may modulate training and transfer gains (see Katz et al. 2021). There is some evidence indicating that particularly conscientiousness is related to transfer effects. Studer-Luethi et al. (2012) found that individuals with higher levels of conscientiousness improved more on near-transfer measures, but surprisingly, less on far transfer tasks. The authors argued that participants with higher levels of conscientiousness may have developed task-specific, nontransferable skills that facilitated success on both the training tasks and a similar near-transfer task but hindered far transfer. Moreover, highly conscientious individuals may experience higher evaluation apprehension on far transfer tasks that could impair performance on these tests.

Studer-Luethi et al. (2016) investigated the moderating effect of the personality traits neuroticism and effortful control on executive function training outcomes in children (mean age = 8.3 years). Participants were allocated to an executive function training group, reading training group, or a no-contact control group. They found a moderation effect of neuroticism and effortful control on transfer gains. The training program predicted higher posttraining gains compared to the reading training group and the control group only in children with high effortful control or low neuroticism. The authors concluded that sufficient self-regulative abilities and emotional stability are necessary for the training to be effective. Likewise, Urbánek and Marček (2016) reported that participants who were more reactive emotionally showed fewer gains on transfer tasks. In sum, these findings indicate that emotion regulation might play an important role in the outcomes of executive function training.

7.3 *Intraindividual Performance Differences During Training*

Aside from interindividual differences, we need to consider intra-individual dynamics and fluctuations in training-induced performance changes. Intra-individual performance trajectories across the training phase can reveal which participants show training effects at all and when they reach their individual maximum. The fluctuations in these trajectories can serve as indicator for adaptive (e.g., varying strategies) or maladaptive processes (e.g., vulnerability to disturbing influences) during the training. Moreover, these performance fluctuations can be coupled with other variables, such as motivation, sleep, or affective processes. Analyzing these couplings can tell us which internal and external factors contribute to individual performances and how much participants differ in the strength of these relations (Könen and Karbach 2015). This seems particularly relevant for studies with heterogeneous samples, such as different age groups or patient samples, because variation in intra-individual effects across training may eventually result in inter-individual differences in training outcomes.

Thus, considering both inter-individual and intra-individual differences and dynamics has the potential to contribute massively to our understanding of training outcomes and can help to generate theories regarding the underlying mechanisms.

8 Application of Multitasking Training

Aside from investigating the transfer effects of multitasking training to other lab-based cognitive tasks, there has been growing interest in assessing effects on the activities of daily living and on cognitive performance in clinical populations with cognitive deficits (for an overview, see Strobach and Karbach 2021). In order to illustrate this more applied aspect of multitasking training, we will present and discuss recent findings of studies targeting academic abilities in children on the one hand and studies assessing the effects of training in clinical populations on the other hand.

Academic abilities, such as reading and mathematical abilities, are involved in many daily activities, and academic achievement in these subjects is predictive for various life outcomes, such as vocational success (Dyer 1987; Rabiner et al. 2016**.** Therefore, much research has aimed at improving academic abilities by targeting the underlying cognitive processes. While many studies have focused on working memory, recent studies also investigated the effects of training of multitasking. These studies were based on findings showing that multitasking ability is an excellent predictor for reading and mathematical abilities (for a meta-analysis, see Yeniad et al. 2013; for a review, see Titz and Karbach 2014). However, other studies suggested that the association between multitasking and academic abilities may vary as a function of the subject of interest (Agostino et al. 2010; Cartwright et al. 2010; Colé et al. 2014; Lee et al. 2009) and even within a given domain. For instance, a recent study assessing the relationship of executive functions to reading ability indicated that children's working memory span and inhibition ability were related to reading speed, whereas multitasking (shifting) ability was positively related to reading comprehension (Johann et al. 2019).

Considering the significant relationship between multitasking and academic abilities, it is conceivable that training multitasking abilities may result in improved academic performance. While there are numerous studies testing the effects of working memory training on academic abilities, only a few have tested the effects of multitasking training. In one of them, 7- to 11-year-old children were trained on executive function tasks (16 sessions), including task switching and the Wisconsin

Card Sorting task. Compared to an active control group, the executive function training resulted in improved reading comprehension at posttest, while no benefits emerged in terms of mathematics (Hadley et al. 2019). The other study systematically investigated the effects of game-based and standard training regimens targeting working memory, inhibition, or multitasking (task switching and dual tasking) in 8–11-year-old children across 21 sessions of training (Johann and Karbach 2020). The design included an immediate posttest and a 6-week follow-up assessment. After the training, the game-based multitasking training showed larger improvements than the control group on a reading task and these benefits were still present at follow-up. Consistent with Hadley et al. (2019), there were no training-related improvements in terms of mathematics. In sum, these studies provide first evidence for positive effects of multitasking on academic abilities. That said, despite these promising findings, multitasking training as a way to boost academic performance is still in its early days and much more research is needed to probe its efficacy in other populations, including other age groups as well as individuals struggling academically, such as children with learning disorders or ADHD.

When it comes to clinical populations, multitasking training has been studied with randomized controlled trials in individuals with autism spectrum disorder (De Vries et al. 2014) and ADHD (Kray et al. 2012; Dovis et al. 2015). A recent meta-analysis reported that near transfer effects of multitasking training were small but significant, but far transfer effects were not significant (Kassai et al. 2019). While the number of studies focusing on multitasking training is limited, existing evidence indicates that alternating between different tasks during cognitive training seems to increase training effectiveness (Buitenweg et al. 2012) and that multitasking training might be most effective when several executive functions are trained simultaneously (Dovis et al. 2015). For instance, a blind randomized controlled trial of a working memory and multitasking training for autistic children with Braingame Brian (De Vries et al. 2014) reported that both the working memory and multitasking training induced near transfer effects, but no transfer to other EFs or daily life. Another study on children with ADHD reported that multitasking training also tapping working memory and inhibition (alternating runs task-switching training with ambiguous stimuli) resulted in near transfer, but additionally in far transfer to inhibition and working memory performance (Kray et al. 2012).

In older age, multitasking training has been studied in individuals with mild cognitive impairment (MCI). Gagnon and Belleville (2012) compared the effects of variable and fixed priority multitasking training (dual-task training) in patients with MCI that experienced executive control impairments. Both training groups showed transfer to measures of focused attention, speed of processing, and task switching, indicating that multitasking training can be effective in older adults with mild cognitive impairments.

Recently, the interest has also been on (mostly but by far not exclusively older) adults suffering from chronic heart failure. Aside from typical physical symptoms, these patients also show significant cognitive impairments, especially in the area of executive control (Kindermann et al. 2012). Given that these cognitive impairments can also have negative consequences for disease management (e.g., because medication is not taken in time or necessary self-monitoring of symptoms fails), there has been a growing interest in compensating these cognitive impairments. A recent randomized controlled trial tested the effects of a combined task-switching and working memory training and found substantial gains on the trained tasks. Moreover, the training transferred to short-term and working memory, episodic memory, and processing speed. These transfer gains were stable across three months, although diminished after six months and most pronounced in low-performing individuals (Wedegärtner et al. 2021).

In sum, there are a number of studies focusing on cognitive training in populations with cognitive deficits related to (neuro-)developmental or physical disorders or pathological aging (see Boller et al. 2021 and De Vries et al. 2021 for reviews), but only very few of them applied multitasking training. These studies indicate that multitasking training may be very promising in order to improve cognitive performance in these populations, but clearly more evidence is needed to disentangle the mechanisms driving these effects and to tailor interventions to specific groups of patients or profiles of cognitive impairment.

9 Conclusion

In this chapter, we reviewed current theoretical frameworks, methodological approaches, and empirical findings on multitasking training, specifically on task-switching and dual-task training. Over the last two decades, numerous studies have provided evidence indicating that multitasking training leads to significant and long-lasting improvements on the trained task. The majority of studies also reported near transfer to untrained multitasking paradigms. These effects were present across a wide range of ages and were often more pronounced in populations with multitasking impairments (in particular task-switching training), such as children, older adults, or clinical samples. Existing studies indicate that the source of these effects may be training-related improvements of the ability to resolve task interference as well as improvements in attention allocation processes and task coordination skills.

However, evidence on far transfer to untrained, but related, cognitive domains (such as working memory or inhibition) is less clear and has inspired heated debates in the community. A key aspect that may help shed light on this diverse pattern of findings is the analysis of individual differences in training outcomes that may support the design of tailored interventions to improve multitasking abilities. Such interventions may not only help to understand the cognitive and neural mechanisms modulating training and transfer effects, but they could also be particularly useful for the applications in clinical and educational settings.

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Training Based on Multitasking – With a Specific Focus on Motor-Cognitive Multitasking

Bettina Wollesen, Hermann Müller, and Claudia Voelcker-Rehage

1 Introduction

In our daily life, we are continuously confronted with challenging cognitive tasks, such as remembering a phone number, discussing certain topics, or planning certain tactics in team sports. In many cases, however, we have to deal with other cognitive or motor tasks running in parallel, such as remembering a shopping list while navigating through a crowded supermarket. The assumption is that in these multitasking situations processing streams of the involved tasks overlap and that performance in such situations is not only limited by the capacity of each single process but also depends on how effectively we manage process interactions (Medeiros-Ward et al. 2015). These multitasking situations can be either situations where persons have to switch between different task demands, i.e., experiencing (multiple) interruptions while performing a cognitively demanding task, or having to perform two tasks simultaneously; for example, an elite athlete performs a motor skill (e.g., dribbling a ball) while concurrently reflecting on tactical decisions. Typically, limitations in processing of multiple tasks as compared to processing a single task (ST) are described. These processing limitations become even more obvious when the overall capacity is limited, like in novices or older adults. In the case of vulnerable groups, such as older adults, limited performance

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or processing capacity might also induce threats to the physical integrity of the person.

Getting rid of the limitations or at least pushing the limits to some extent in order to either (a) maintain performance despite disrupting/simultaneous secondary tasks (dual-task scenarios) to optimize performance in specific multitasking settings or (b) to counteract decline in relevant processing capacity has a high functional relevance for different target groups (e.g., athletes, older adults, employees) and has therefore been the target of many research studies. To design suitable training regimes, one needs to identify the particular processing components which actually cause the limitation and try to modify the functionality of these processes through specific interventions.

In this chapter, we particularly focus on the interaction of cognitive and motor processes. These are situations where at least one of the tasks involves a motor action with substantial requirements on movement control; these are often continuous movements with high demands on spatial accuracy requiring the integration of multiple sensory signals. Multitasking scenarios comprising such "complex" movements are representative of the actual multitasking challenges we encounter when navigating and operating in real-world settings, including activities like driving or walking in which our health may be threatened in case of failure. Due to the importance of successful operation in these situations, many studies have already addressed the question, how cognitive motor dual-task abilities can be modified by cognitive-motor training.

The first step of identifying relevant sub-processes for a given performance goal in a particular multitasking setting is far from trivial, since successful execution of the task combination requires the interplay between several conscious, subconscious, and unconscious cognitive and motor processes and is influenced by psychological moderators such as emotion, motivation, and volition. Therefore, in Sect. 2 we will present different theoretical approaches suggesting conceptualizations of relevant sub-processes for (cognitive-motor) multitasking. Most of these sub-processes are considered to be adaptive or plastic, i.e., the functionality of a particular process changes in a use-dependent way. To induce these changes in the targeted direction and to the desired extent, one needs to properly design the interventions according to the goals and the current status of the trainee. That is, the amount of change might depend on particular features of the practice episodes. Thus, in Sect. 3, we will develop general principles that need to be obeyed when planning and conducting training interventions. Section 4 will give a structured overview on existing literature on training studies on cognitive-motor dual tasking. Studies are clustered based on typical training settings such as specific and general dual- or multitasking training and with respect to task-managing strategies. Also computerized or virtual training regimes will be described. Finally, in Sect. 5, we will summarize all relevant findings and give some practical implications and recommendations for future interventions.

2 Basic Concepts Underlying Multitasking Training – Task Constraints, Processes, and Plasticity

People undergo multitasking training to modify performance in targeted aspects. A general idea is that the current performance level is confined by a limited capacity in at least one crucial processing component (Wickens 1980). This component should be specifically strained during training and, consequently, will poteniallyy increase its functional capacity in the long run. For this to work, (a) the limiting process has to be identified correctly; (b) as a crucial precondition, this process itself should be sufficiently modifiable; and c) the training protocol needs to be defined properly to actually address the relevant process. In the following (Sect. 2.1), we will mention different conceptualizations of how relevant (sub)processes of multitasking can be candidates for potentially limiting process components. In Sect. 2.2 we will discuss in an exemplary fashion how and to which extent changes in functionality of these processes might be modeled. Finally, Sect. 2.3 describes how task constraints might affect the degree to which (sub)processes need to be considered in certain tasks or task combinations when designing training procedures to train the targeted component.

2.1 Different Approaches Explaining Performance Limitations

One prominent example to illustrate ongoing processes and actions in a multitasking situation is cooking a dish. Salvucci and Taatgen (2008) suggest using imagery storyboards to describe the required cognitive-motor actions to manage a multitasking situation. They illustrate this storyboard by the example of cooking a dish, that is, all ongoing processes and actions required in a certain multitasking situation are listed that need to be integrated to complete a meal. The different components for cooking a dish need to be analyzed due to their requirements of relevant timelines and cognitive-motor actions to composite the whole dish to be ready at the same time. For example, in the timeline of cooking fish, pasta, and a cake in parallel, different processes subserving different subgoals and actions are required (Salvucci and Taatgen 2008).

However, due to limited resources of equipment and time, the timeline also has to be fitted into the available resources (e.g., how many things can be in an oven at the same time? How many pots can a person carry and handle at the same time?). Transferring this example to, for instance, the work context, employees need to trade off time against equipment limitations to find an optimal scheduling while switching between activities, such as making phone calls, using computers, supervising machine operations, or even trying to manage several subtasks in parallel (Spink et al. 2008). These examples illustrate that successful performance in a multitasking situation depends on an effective operation of several sub-processes. Some of these processes are directly included in the processing stream of the single tasks, whereas additional meta-processes, like goal setting, prioritization, scheduling, resource allocation, or evaluation, are operating at different levels to secure the interplay of all sub-processes (e.g., Burgess et al. 2000). The concept of imagining a storyboard of all relevant task constraints is also useful for planning an adequate cognitive-motor training intervention. To gain the highest benefits, all training goals should be set with respect to the relevance of each component (cf. Sect. 3).

Several models have been developed to describe cognitive processes involved in multitasking situations. These models differ with respect to the number and type of categorical subdivisions of processing components (e.g., Wickens 1980; Baddeley 1996) and the strictness of the capacity limitation of each component. This includes different assumptions regarding the degree to which the sequence of the assumed processing stages is either completely fixed (as in the Psychological Refractory Period (PRP) model, Pashler 1984) or is automatically adjusted to certain task constraints (as in the Adaptive Control of Thought (ACT-R) model, Anderson et al. 1998, or Executive-Process Interactive Control (EPIC) model, Kieras and Meyer 1997) or can flexibly be controlled by meta-processes (as in the Threaded Cognition Theory, Salvucci and Taatgen 2008). According to these different model approaches, different causes for observed performance limitations can be identified. However, common to all concepts is that performance decrements in multitasking situations are typically explained based on two fundamental assumptions: (a) quality of performance is directly related to the quantity of the deployed processing activity and (b) this processing quantity is limited. Some models explicitly state which quantity they refer to (e.g., processing time in the central bottleneck stage; Pashler 1984), whereas others rely on the concept of resources (Wickens 1980). Most commonly, the models postulate more than one process or more than one type of resource, each having its own quantity limitations.

Performance decrements under multitasking conditions arise if two tasks compete for access to the same process/resource. This competition can be modelled as an all or none allocation by an automatic process (e.g., "first come first serve," PRP; Pashler 1994) or as being controlled by a meta-process. Others presume a more or less graded sharing of resources dependent on certain features of the task (e.g., Wickens 1980) and/or internal prioritizations (e.g., Norman and Shallice 1986).

The PRP paradigm allows powerful explanations and precise predictions in a clearly defined experimental setting; however, identifying limiting process components is far more difficult in less restricted situations like real-world cognitive-motor dual tasks (DT), for instance, driving while having a conversation. Given the complexity of the tasks and the multitude of potential, flexibly concerted, but mostly unobservable sub-processes, it seems impossible to pin down a certain processing component as the ultimate origin of interference. In lieu thereof, a more abstract concept of a limiting *processing capacity* has been developed (Broeker et al. 2018). The central concept is the idea of a *resource*, which is understood as a general capacity, required for information processing in a certain domain. The model assumes that concurrently operated multiple tasks compete for resources. Performance limitations arise because the pool of resources is limited. In case of a rivalry, cognitive processes for separate subtasks cannot run simultaneously, but sometimes in series (Kahneman 1973; Wickens 1980). However, this competition is domain specific. According to Wickens' model, interference rises whenever tasks require similar sensory modalities and information channels (Wickens 1980). Accordingly, less interference should occur when different sensory modalities or response reactions are taking place in parallel in contrast to cases with tasks requiring similar modalities or motor reactions.

Resource allocation is driven by the requirements of the task. To give a simple example, it may be important whether processing involves object-based (e.g., the discrimination of stimulus attributes) or spatial attention (e.g., the localization of stimuli; Wahn and König 2017). In Sect. 2.3, we will come back to the connection between task features and resource allocation in more detail but in an instrumental, thus reversed, causal relation.

The Wickens model (Wickens 1980) also assumes requirements for an organizational process in the central nervous system to distribute resources to each of the competing processes. For the allocation of attentional resources, Norman and Shallice (1986) suggested the presence of a supervisory attentional system (SAS), and Baddeley (1996) described a *central executive system* that organizes the resource allocation. This system has three functions: task switching, memory updating, and response inhibition (Baddeley 1996; Miyake et al. 2000; Strobach et al. 2014). Multitasking has also been suggested to be an executive function itself (*executive function of "dual tasking"*) rather than being a process consisting of the three functions named above (Strobach et al. 2014; Enriquez-Geppert et al. 2013). Irrespective of the details of different models, ultimately, externally imposed task demands and internally generated task prioritizations will define how individuals allocate resources to reach the most desirable outcome.

The idea of the *theory of threaded cognition* (Salvucci and Taatgen 2008) is based on three different types of resources. These are cognitive, perceptual, and motor resources. The cognitive resources are subdivided into procedural and declarative resources. The procedural resources describe procedural skills as goal direction rules. The declarative resources describe static knowledge and information chunks. Perceptual and motor resources represent information acquisition from the environment and allow interaction with the environment. Within each resource category (cognitive, perceptual, and motor), information processing is executed serially and can only answer to one thread at a time. If there is a resource allocation conflict for procedural resources, the least recently processed thread will be pushed forward. In addition, Salvucci et al. (2009) suggested an "imaginal module (holds representations of the tasks requirements)" and a "procedural module (taking all information of different processing stages into account)". Since this model, other than "pure cognitive" models assuming a conflict exclusively at central processing stages, this model explicitly includes the possibility of interference at a motor stage; therefore, it is of relevance for cognitive-motor multitasking.

As already mentioned, resource attribution is not only driven by task requirements; therefore, the list of relevant functions in multitasking management is extended by factors dealing with internal preferences and dispositions inside the acting person like goal setting, planning, and decision-making or emotions, respectively, affective states (e.g., Burgess et al. 2000). Along that line, comparable cognitive abilities related to intelligence, knowledge, and recollection of expected tasks have also been mentioned as potential factors underlying cognitive-motor interactions.

Moderating or Mediating Factors of Multitasking Performance

In order to define appropriate training goals, the cognitive abilities that need to be managed to reach the task goal have to be identified by looking at the different task sets or storyboards.

Especially *executive functions* (EF) are discussed as factors that might moderate or mediate dual-/multitasking performance (Yogev-Seligmann et al. 2008). According to the definition of Diamond (2013), EF is an umbrella term for a collection of mental processes regarding the ability to concentrate, focus, and adequately react to external stimuli. Based on this, it is of general agreement that EFs are subdivided into at least three core elements (Diamond 2013; Miyake and Friedmann 2012). *Inhibition* describes the ability to control attentional resources, for example, connected to behavior, thoughts, or emotions. Inhibition enables us to selectively focus on an external stimulus to be processed, while suppressing other stimuli. *Working memory* (WM) or updating involves holding and manipulating information in mind, for instance, using stored information to solve an ongoing problem. Linked to a variety of neuronal subsystems, WM enables to analyze and cluster information while selectively focusing on information stored in mind. WM often requires reordering stored information, for example, repeating a selection of numbers in another order (which is used in complex digit span-backwards tasks, e.g., the n-back task). *Cognitive flexibility* describes the ability to change perspectives according to external demands and in order to produce an adequate reaction. Flexibility is often investigated via task-switching (set-shifting) tasks. This requires, for example, the ability to rapidly shift between various required stimulus-response sets (e.g., during the Wisconsin Sorting Card test, Falbo et al. 2016). Other theoretical concepts rely on similar but also partially different classifications. The list of relevant EFs is extended by concepts like reasoning (Buehner et al. 2006), executive memory (confabulation, preservation, Burgess et al. 2000), or visuospatial abilities that are connected to the processing and memory of visual as well as spatial stimuli at the same time.

According to Endsley (1995), *situation awareness* is another relevant factor, implying the three following process requirements: (1) perceiving all relevant objects in a given environment (e.g., identifying objects indicated on the monitor), (2) understanding the meaning of all identified objects and the interpretation of the situation (e.g., users have to understand displayed information and, maybe, even need to integrate information into their existing knowledge), and (3) predicting the changes of the object's state and of the environment for a certain time span.

Moreover, for cognitive-motor performance, Wulf et al. (2010) emphasize the influence of the *focus of attention* on performance of movements with respect to effectiveness (precision and consistency of task execution; external focus) and efficiency (e.g., muscle activity, physical effort, cardiovascular stress required to execute the task, internal focus). Results of cognitive-motor performance are far better when the attention is focused on external effects of the motion execution than when the execution of movements is focused internally.

Another important aspect of multitasking management is *prospective memory*. According to Fronda et al. (2020), the process of prospective memory integrates intention, formation, retention, re-instantiation (programming of for example motor responses), and execution. The authors also revealed an interdependence between working memory and prospective memory for complex task conditions (Fronda et al. 2020). Therefore, prospective memory is, for example, necessary to process information of watching traffic in the environment or planning future movements of objects (Spiers and Maguire 2007). Other studies introduced the concept of *polychronicity*, which is more a general attitude on how to act in multitasking situations (Courage et al. 2015). The review by Courage et al. (2015) describes this factor as the extent to which individuals prefer to be engaged in two or more tasks at the same time, based on their belief that this is the best way to get things done. This implies personal traits like extroversion, agreeableness, general mental ability, openness, stress tolerance, achievement striving, and Type A personality (Courage et al. 2015). Finally, there is evidence that *emotional aspects* will have an impact on the execution process. The OPTIMAL theory (Optimizing Performance through Intrinsic Motivation and Attention for Learning) by Wulf and Lewthwaite (2016) includes the assumption that an individual's motor execution and motor learning are affected by their attentional focus, motivation, expectations, and feeling of autonomy.

More information on all these different approaches can be found in the other chapters of this handbook in more detail, for instance, chapter "The multitasking motorist" (Reddick) on individual differences. Yet, we decided to include the overview above to clarify how many differently conceptualized sub-processes are involved in successful multitasking, making it very difficult to identify the sources of interference and limitations in relevant processes. In the context of training, this multitude of alternatives entails the problem to decide which processing component(s) of the cognitive-motor system should be targeted during training. In addition, given the diversity across trainees in a large number of modulating factors, it cannot be taken for granted that any particular training regime will always actually address the same target processes in all persons. A proper conceptual description of the limiting sub-processes in a particular situation is also important to delineate expectations to which extent the functionality of any crucial sub-process might be improved at all or how far any training-induced improvements may also be accompanied by performance improvement in other non-practiced situations (transfer). In the following sections, we will try to outline basic ideas on how the functionality of these processes may change during practice. As stated earlier, in doing so, we will particularly focus on cognitive-motor multitasking situations, since these, given their more complex nature, can be expected to be more prone to complex interactions of modulating factors.

2.2 Plasticity

A fundamental property of our cognitive functioning is that it is adaptive, meaning it is capable to change its functionality. This can be seen as a change in performance, more detailed signs of improved function of a sub-process, or even structural changes in our brain and body. We will call this general ability to adjust the functionality of the system *plasticity*. However, there might be differences, to which degree a particular system may change its functionality, or stated differently, to which degree a system is "plastic." Therefore, when planning a training intervention, it is important to have an estimate of the amount of plasticity and of its time course. When deciding which component to select as training target, one would always prefer highly plastic components adapting within relatively short periods over components that develop poorly and slowly. Therefore, it is helpful to discuss how plasticity in relevant sub-processes may affect performance.

According to the fundamental assumptions in resource theories, resources are considered as a quantity of processing capacity, each process calling for a certain share of such a limited quantity. Quality of performance can also be expressed as a quantitative value, and, most importantly, one would expect that such a performance quantity is positively related to the resource quantity available to crucial sub-processes. In this section we will address the question how we can conceive performance improvements in such a line of thought. Essentially, there are – besides others – three basic alternative assumptions discussed (e.g., Von Bastian and Oberauer 2014; Strobach and Schubert 2017): (a) *increased capacity*, the quantity of resources is increased, i.e., the limit is raised; (b) *higher efficiency*, the processes become more efficient, i.e., per unit of processing quantity results a larger quantity of performance; or (c) *optimized task management*, resource allocation is optimized, i.e., resources are better allocated to the most crucial sub-processes.

2.2.1 Increased Capacity

The idea of a training-induced increase in capacity is often tightly linked to the concept of neuroplasticity. Networks of neurons are expected to have higher processing capacity; the better the neurons are connected, the better the nutrient supply is. Cognitive-motor multitasking training is thought to be suitable to induce changes in the processing capacity in the brain, for example, synaptic changes, facilitating cognitive processing. One assumption in this context is that simultaneous training of physical and cognitive tasks has positive synergistic effects that exceed the effects of pure cognitive training or cardiovascular or motor coordination training alone (Kraft 2012; Fissler et al. 2013), whereby mechanisms of training might substantially differ. Neurobiological effects typically described as induced by physical training protocols are as follows:

- Synaptogenesis, synaptic potentiation, and reorganization of movement representations within the motor cortex. These seem to be affected by motor skill training and/or motor coordination exercises (but also cognitive exercise).

- Angiogenesis, leading to increased brain vascularization and cerebral blood flow. This seems to be particularly induced by endurance (cardiovascular) training but does not necessarily alter motor map organization or synapse number directly.
- Elevated neurotrophic factor levels, most importantly BDNF (brain-derived neurotrophic factor), IGF-I (insulin-like growth factor), and VEGF (vascular-endothelial factor). These contribute to structural brain changes by promoting synaptogenesis, neurogenesis, and angiogenesis and have been related to cognitive and physical exercise.

Whether and how these processes are similarly or even more pronounced induced by combined cognitive-motor training requires further research. In this vein, Herold et al. (2018) introduced a *guided plasticity facilitation* framework to explain advantages of physical-cognitive training settings. They suggest that additive synergistic effects emerge from the facilitation effects of physical exercises and the *guidance effects* of cognitive exercises (Herold et al. 2018). Physical exercises should boost the neurophysiological mechanisms that are associated with neuroplasticity (Fissler et al. 2013), whereas cognitive training seems to enable the functional integration of new neuronal structures in the respective brain circuits (Voelcker-Rehage and Niemann 2013). Herewith, we need to carefully distinguish between different physical/motor-cognitive training approaches, (a) with respect to the exercise intensity, duration, and frequency, (b) type of exercise, (c) paradigm/delivery mode (e.g., walking while thinking or thinking while walking), and (d) dual-task setting (cf. Sect. 3).

2.2.2 Higher Efficiency

The idea of higher efficiency does not necessarily imply that the respective process provides the same performance with an overall lower quantity of resources. Of course, this may also be possible. However, the most prominent concept in that respect is automaticity. The basic assumption is that processing is taken over by a separate, task-specific processing pipeline, reducing the need for central resources. Thus, more automatic processing can be seen as being more efficient in terms of its lower use of limited central resources.

The concept of *task automatization* has a long tradition in the area of motor learning. A general characteristic of the motor system is that we can perform certain well-learned movements rather automatically, i.e., without involvement of central resources or conscious processing. That is, automated movements are performed without attention being clearly directed toward the details of the movement (Bernstein 1967). Automatic processing of these movement patterns is fast, demands few central resources, and may also be executed without persons actually being aware of any processing activity. In contrast to automatic movement patterns, controlled movement patterns require ongoing adjustments to primary objectives, deliberate selection of matching movements, and inhibition of those that do not fit. Nonautomatic movements need supervision and control by attentional or working memory processes.

Hence, especially newly learned movement patterns and those that, which frequently need to be adjusted, require special attention (Karnath and Thier 2012), i.e., cognitive processes. However, after extended periods of training, typically, even complex tasks can be executed automatically (Wu et al. 2004). For example, musicians can perform music accurately while holding a conversation (Wu et al. 2004).

Automatization of a task reduces its need for shared central resources. Following the general idea that biological systems adapt to strain by increasing the capacity or the strained subsystem, one could also interpret automatization as an adaptation to strain. In this case, one would assume that a high demand of resources will induce adaptive processes trying to reduce the negative effects of resource limitations. Hence, one could conjecture that the process of automatization is driven by an experienced episode of lack of resources. According to this rationale, one would expect that automatization is boosted if a lack of resources becomes apparent in a multitasking setting. Therefore, automatization is a very relevant concept, which we need to keep in mind when discussing the empirical studies on motor-cognitive multitasking training in Sect. 4. Furthermore, multitasking settings may not only be instrumental to train tasks and to induce automaticity; they can also be a means to evaluate to which degree automaticity is actually achieved (Wu et al. 2004). The basic idea is that as long as a task is not performed automatically, it is still calling for its share of limited central resources and that dual-task decrements will occur if the task is performed in parallel with a secondary task also calling for the same resources. Accordingly, the observation that two tasks can be performed simultaneously with minimal or no interference is interpreted in a way that at least one task is considered to be performed automatically (Passingham 1996). Cognitive-motor task performance should improve if a certain task is trained or practiced until the dual-task-related decrements have disappeared (Ruthruff et al. 2006).

2.2.3 Optimized Task Management

Successful multitasking might be accompanied with an emergence of so-called task-managing strategies, helping to deal with concurrent multitasking settings, for example, via task switching or sequential multitasking according to an increasingly smart prioritization of tasks. In addition, automatization of certain task components might allow a flexible focus on crucial subgoals. Within a training intervention, these processes might be supported by adequately designed task instructions, which help to optimize the internal goal settings of the system (e.g., if you want to catch a ball on a moving platform, it would be relevant to get a stable position before preparing the catching of the ball).

Different authors have suggested specifications of the processes involved in task management (Salvucci and Taatgen 2008; Burgess et al. 2000; Bherer et al. 2005; Wollesen et al. 2015, 2017a). These processes integrate the following steps:

- Information processing of necessary stimulus intake according to the task environment

- Goal planning for the multitasking situation, identifying subgoals, storyboards, and timelines
- Resource allocation for the different activation levels of the storyboards and timelines
- Task-managing strategies to execute the storyboard and timeline requirements

Following a slightly different approach, Burgess et al. (2000) named five relevant factors for multitasking performance in the work context that are related to the task management approach and might be transferable into situations of daily life or (sport) specific situations that focus on cognitive-motor dual tasking: (1) inhibition (response suppression and distinction), (2) intentionality (planning and decision-making), (3) executive memory (confabulation, preservation), (4) positive affective changes, and (5) negative affective changes. To organize the interplay between these components, the task-managing process requires ongoing planning, reassessment of goals, re-prioritization, and re-scheduling (Burgess et al. 2000). Moreover, the planning process involves the ability to create and activate delayed intentions for the multiple subgoals of the internal schedule (Burgess et al. 2000). As there are individual differences in these abilities, one might assume that tailored multitasking interventions or training regimes will have a positive impact on these task management abilities and cognitive processes.

2.3 Task Constraints

So far, we have introduced the basic idea of training as a designed intervention, applied to train a targeted processing component with the final goal to improve its functional capacity, efficiency, and task management. We also gave an overview on potential candidate processes which could serve as a target and presented general conceptions of the nature of changes in functionality that may occur. However, a major problem remains: most of the processes are not directly observable. In these cases, it remains unclear whether the targeted process is adequately trained by a given task or task combination. This problem is even magnified by the fact that training interventions do not only need to be specifically tailored to the respective training goal, but they also have to be adjusted to the performance level of the trainees and the overall training conditions, like training environment, material, and time constraints. Imagine, for example, a motor-cognitive gait training. This needs to be differently designed depending on whether the aim is to improve cognitive performance under motor-cognitive gait situations or to prevent falls in older adults, or whether it aims to support arithmetic performance in kindergarten children. Since, as already said, the strain level of demands on the processes is not directly observable, one needs to adhere to more general principles, particularly, the idea that certain features of the task are systematically linked to effects on certain sub-processes (for example, if you have to read a sign during a balancing task, the body sway has to be minimized to focus the letters on the sign).

In order to effectively train a certain processing component, it is very important to induce a certain amount of processing activity in the targeted component. However, in a training session, the trainer has no direct control over the actual activity inside the trainee's head. The trainer can only try to adjust the training conditions in a way that the desired processing activity most likely will be initiated. In the following paragraphs, we will list several task categories, which are assumed to impose specific constraints which will (hopefully) induce specific cognitive-motor processing regimes in the trainees.

A major factor affecting the type of processing is the *temporal characteristic* of the tasks. In speeded tasks requiring just one single response, processing is locked to a very short time window. This allows relatively low temporal flexibility compared to settings with less strict time constraints. In multitasking settings, not only the temporal characteristics of each separate task matters but also the degree to which tasks actually overlap in time. Taking these aspects into account, Salvucci (2005) has separated four categories:

(1) Serial discrete tasks (i.e., task-switching)
(2) Simultaneous discrete tasks (i.e., overlapping tasks)
(3) Continuous tasks (interrupted only by occasional discrete tasks)
(4) Composite (simultaneous) continuous tasks

For example, in speeded discrete tasks, the temporal aspects of the processing regime and the underlying allocation of resources are mainly driven by the temporal constraints imposed by the stimuli. The limited time available for task completion limits the degree of flexibility in shifting and postponing sub-processes in time (e.g., Pashler et al. 2001; Rubenstein et al. 2001). This also holds for task interruptions (e.g., Janssen et al. 2015; Janssen and Brumby 2015), particularly in cases where the interrupting task must be executed immediately.

Continuous tasks allow higher temporal flexibility, so that we can assume that temporal management may be of particular importance in the latter case. Accordingly, one would recommend using continuous training tasks when targeting this aspect. Therefore, in Sect. 4, we will report on related cognitive-motor training interventions using a primary continuous motor task.

In a recent review regarding different types of motor-cognitive training in older adults (sequentially vs. simultaneously), Tait et al. (2017) revealed that simultaneously executed cognitive-motor training was more effective to improve cognitive-motor performance than sequentially conducted exercises. Herold et al. (2019) as well as Tait et al. (2017) explain these results with the idea that different time intervals may activate different neurobiological pathways. These pathways use different neurophysiological mechanism (cf. Herold et al. 2018). By suitably arranging the temporal sequence of cognitive and motor tasks, neuroplasticity and the resulting structural and functional brain changes can be optimized. Herold et al. (2018) assume that simultaneous cognitive and motor activity combines physical facilitation and cognitive guidance effects due to their temporal synchronization, thus increasing neuroplasticity and performance (also see Tait et al. 2017). With respect to task constraints, specific training interventions initiating mental stimulation as well as mental compensation (e.g., with specific cognitive training like the method of loci) can enhance neural plasticity (Baltes et al. 1999; Park and Bischof 2013).

So far, we have only discussed temporal characteristics in an exemplary fashion. However, there are a lot more task features but also *factors* inherent to the trained person *that modulate training outcome* by imposing specific constraints on task processing. A selection of these will be briefly mentioned in the following section.

One important aspect is the *number of simultaneous tasks,* respectively, the number of alternating episodes of multitasking situations (Janssen et al. 2015; Rubenstein et al. 2001). Besides the number of tasks, the number of decisions that need to be taken in each of these tasks is also of importance, particularly if these decisions need to be arranged in a *meaningful sequence*. In this case, it is of utmost importance that people can anticipate future conditions of the system. An umbrella term often mentioned in this context is *task complexity*, which, however, is ill defined in most cases. Even though there might be a general agreement that complexity should be related to the number of tasks, the number of sub-processes, and/or an intricate temporal structure, it is often difficult to pin down which specific processes are actually involved. The degree to which the acting person is free to organize task processing is defined by task constraints but is also determined by more trait-like *individual preferences for task organization* (involving more or less serial or partially overlapping processing). The study findings of Reissland and Manzey (2016) showed no general self-organization benefit in task-efficiency but a reduction in multitasking costs for people with a preference for overlapping processing. These results were supported by Bachmann et al. (2019) who revealed that larger multitasking autonomy reduces performance decrements under multitasking conditions. This is one example of personal factors (individual constraints) modulating the effect of certain task constraints in the way task processing is actually organized. Emotion, motivation (cf. OPTIMAL theory), age, or expertise might be further aspects that need to be considered. Furthermore, these factors underlie changes on different time scales. Whereas emotions may change almost immediately, be it due to task-related events (e.g., success, failure) or internal causes unrelated to the task (e.g., mood), other preferences will only change on a longer time scale, possibly based on accumulated experiences.

In summary, all these task-related and person-related factors will interact, setting up a so-called *conflict matrix*. Since the resulting cognitive-motor interference can occur at all stages of the multitasking process (information processing, goal planning or scheduling, resource allocation, and task execution), such a matrix would be helpful to estimate the strain level of different sub-processes. The more valid these estimates reflect the actual interference profile in a certain task combination for a given person, the more specific multitasking training protocols can be designed based on such a conflict matrix.

3 Basic Principles of Cognitive-Motor Multitasking Training (CMT)

It is quite common in cognitive as well as in exercise science that we expect an improvement in performance when we practice a particular task, or in our case a certain task combination, sufficiently often. This improvement is typically explained by the assumption that at least one of the underlying processes has changed its functionality. In most cases, however, no theoretical idea exists how this change in functionality occurs. Rather than having any elaborated model, explanations rely on the belief that a limited number of basic principles hold true which allow the deduction of a few fundamental training principles according to well-accepted knowledge in exercise science.

3.1 Training Principles

Following general principles of training and mostly in lack of a mechanistic model of how the plastic changes are actually affected, training should be designed according to these principles derived from exercise and training science in order to be most effective (Herold et al. 2019; Wollesen et al. 2020). Although these principles are derived from exercise science, they could set a ground for the planning and conduction of cognitive-motor training.

A common rationale is the following, building on *two axioms* (A1, A2) which are used to derive *seven principles* (P1 to P7), cf. Table 1:

A1: *Specific adaptation to task demands*: Humans, like most other biological systems, are shaped by evolution in a way that they adapt to strain. In general, the performance capacity of any subsystem is adjusted to the degree to which it is used. Increased use will lead to improvements in the functionality of the subsystem, enabling it to exhibit higher performance in the future. On the other side, lack of use will lead to a loss in performance capacity. The important fact is that this adaptation is specific, only the trained subsystems will adapt.

A2: *Optimal intensity*: Gains and losses in performance capacity are not necessarily linearly related to the quantity of use. At least in some cases, maximal use might even be detrimental for the future performance capacity (*overuse*). Rather, submaximal demands will lead to the highest long-term gains in performance. The degree to which an existing performance capacity is utilized is called i*ntensity* in this context. In exercise science, intensity is often quantified as the percentage of maximum performance.

The following principles are more or less straightforward deductions, unfolding from these two fundamental axioms:

P1: *Specificity*: As a direct consequence of A1, training should specifically tap the targeted performance components. To elicit a desired adaptation, the contents of the exercises must be tailored to train the targeted performance components.

Table 1 General principles relevant in a training program

P1 Task specificity	To elicit a desired adaptation, the contents of the exercises must be tailored to train the targeted performance components
P2 Optimal intensity	Intensity is typically defined as a proportion of maximum performance. Yet, the optimal percentage can vary, for example, between experts and novices. It is dependent on the person's individual development as well as their tolerance to strain
P3 Progression	To ensure continuous improvements, the stimulus must be appropriately modified over time (e.g., increase in external load). Best practice recommendations for the order of the progression are (1) increasing the number of training sessions, (2) increasing the duration of a session, and (3) increasing the intensity
P4 Control	Compliance with the planned intensity needs to be monitored intermittently during training and, in case of a deviation, be corrected
P5 Reversibility	Once the training intervention induced stimulus is removed (e.g., stop the training), de-adaptational processes in physical functioning will occur, and the functional level will eventually return to baseline
P6 Periodization, programming, and scheduling	Periodization and programming are crucial elements for an appropriate exercise prescription. Periodization is also referred to as macromanagement, i.e., the temporal coordination of training episodes with specific training goals and contents. Programming describes the organization of exercise variables and training variables (micromanagement). The determination of the temporal microstructure of practice episodes (duration of and temporal distance between single work and rest episodes) is called scheduling
P7 Variation	To increase flexibility, extend and prolong adaptation, and in order to avoid monotony over a distinct training duration, systematic manipulation (variation) of exercise variables and training variables is necessary

P2: *Individuality*: Since individual capabilities may differ between different persons and the optimal intensity being constant at a given percentage of maximum performance, the training load or the task difficulty needs to be adjusted. High-performing trainees require more difficult training tasks than low performers. In order to do so, the subject's performance level needs to be assessed before the training load is defined.

P3: *Progression*: Additionally, training load also needs to be adjusted at the within-subject level. If, during a long-term training, performance improves, task difficulty needs to be progressively increased to secure optimal training intensity and thus optimal gains. In cognitive training literature, this is termed adaptive training (cf. Karbach & Strobach, this handbook).

P4: *Contro*l: Since performance capacity might also change rapidly due to short-term factors like warm-up, fatigue, or psychological factors, compliance with the planned intensity needs to be monitored intermittently during training and, in case of a deviation, be corrected. A cognitive training would therefore integrate a familiarization process as well as a control for fluctuations in the individuals' momentary performance level.

P5: *Reversibility*: Implied by A1 is the assumption that any subsystem that is not used sufficiently will show a decrease in functionality. Once training is stopped and training stimulus is removed, de-adaptational processes in physical functioning will occur, and the functional level will eventually return to baseline.

P6: *Periodization*: In cases where more than one processing component (e.g., A, B, C) needs to be developed, each requiring its specific training (T_A, T_B, T_C,), questions arise on how to arrange periods of training in time. How tightly can two training regimes be temporally interwoven? If this turns out to be difficult, which training should be focused first? When should one switch to the next? Among others, answers to these questions need to consider whether components build on each other but also how gains in the focused component trades off with potential losses in (temporarily) untrained components. Another relevant factor connected with periodization is the scheduling of training sessions if more than one training goal is pursued in close temporal succession. How shall different contents be arranged in time to optimize overall outcome? This may also relate to the question, how motivation can be kept up throughout practice by varying contents and thus avoid monotony. Therefore, periodization and programming are crucial elements for an appropriate exercise prescription. Periodization is also referred to as *macromanagement*, i.e., the temporal coordination of training episodes with specific training goals and contents. Programming describes the organization of exercise variables and training variables (*micromanagement*). The determination of the temporal microstructure of practice episodes (duration of and temporal distance between single work and rest episodes) is called scheduling.

P7: *Variation*: Skills are trained for later use in mastering future (multitasking) challenges. Typically, these challenges may vary to some extent, requiring a flexible use of the acquired skills. Introducing a certain amount of variation in practice helps to develop such flexibility. Furthermore, a certain amount of variability in practice might even contribute to more stable memory traces and extend the adaptive range (cf. Karbach & Strobach, this handbook). Table 1 gives an overview on relevant principles.

The principles listed above lead to four *control factors (S1 to S 4; cf. Table 2)* that need to be integrated for each single training session. These are S1 training intensity, S2 duration of the exercise or the density of exercise bouts in relation to periods of rest, S3 training control, and S4 type of exercise. Like in the case of P2 optimal intensity, the actual magnitude of these parameters will affect training outcome, while a particular value is considered to be optimal for a given training scenario (Erickson et al. 2019; Hecksteden et al. 2018; Herold et al. 2019).

Table 2 lists factors to control training dose in single training sessions in that context.

These exercise and training principles can be supported by specific instructions guiding the processes of performance control. One example for this guiding process can be found within the studies to improve cognitive-motor performance for older adults with an increased risk of falling. The task-managing cognitive-motor interventions by Wollesen et al. (2015, 2017a, b) for older adults included an analysis of different daily movements while walking that might induce a risk of falling (I1–I4 cf. Table 3). Moreover, it integrated explicit explanations by the instructors to introduce awareness of trip hazards, speeds required, and additional tasks (including visual and proprioceptive). Additionally, they were encouraged to focus on active

Table 2 Exercise variables relevant in a single session

S1 Exercise intensity	The exercise intensity describes how strenuous the exercise is. This includes the intensity, amount, and interval of stimuli. The stimuli can be expressed by distances, weights, time, and number of repetitions
S2 Exercise duration	Time period that is spent for a specific exercise or the entire exercise session. This needs to be specified for the cognitive and motor components of the training intervention
S3 Training control	The amount and intensity of a training should be managed with specific markers for exhaustion (e.g., BORG scale, heart rate, lactate concentration, or blood oxygenation in the brain)
S4 Type of exercise	Type(s) of exercise(s) used in the exercise session (e.g., cycling, dancing) need(s) to integrate the storyboard and subgoals
General training variables relevant in a training program	
Frequency	The number of training sessions across a distinct time interval
Density	Distribution of training sessions across a distinct time interval with regard to recovery time in between training sessions
Duration	Duration over which a training program is carried out

rolling movements of their feet to maintain a stable gait pattern. The instructor educated participants about task-managing strategies to assist them in recovering their balance during disturbances (cf. Table 3).

The integration of these strategies into a motor task depends on the task setting, the goals of the movements, and the belonging subtasks. Therefore, according to the training goals and the nature of the multitasking scenario that needs to be performed, the instructions I1–I4 need to be adapted and verbalized.

3.2 Basic Types of Cognitive-Motor Multitasking Training (CMT)

As demonstrated by the examples mentioned so far, many everyday tasks, professional activities or competitive challenges, require a sustained effort to improve skills and maintain or even increase performance in cognitive-motor multitasking situations. Given that the processes affecting this performance are more or less adaptive, i.e., they change in a use-dependent way, we need to find practice regimes that induce the targeted changes in the most effective manner. There is some evidence that the combination of physical and cognitive exercise (cognitive-motor training, either simultaneously or successively) can result in higher benefits in cognitive and motor performance, thus improving overall dual-task performance, than both training regimes (cognitive or motor training) alone (Bamidis et al. 2015; Tait et al. 2017; Zhu et al. 2016). Accordingly, combined interventions have been developed to maximize training efficiency for cognitive and motor benefits (Bamidis et al. 2015). Moreover, there is rising evidence that the training might be most effective if the cognitive and motor components are trained simultaneously either as a

Table 3 Examples of strategies relevant for task managing in fall prevention

I1 Visuospatial strategy	"If there are obstacles in your way, try to recognize the whole area around you and your feet"
I2 Goal setting strategies to recover or maintain balance	"If there are obstacles in your way, it is better to use a foot rolling movement because that way you will not trip over the obstacle" "If you recognize an increased postural sway, increase your base of support" "If you recognize that you may lose your balance, increase your base of support" "If you recognize that you may lose your balance, use a sidestep to recover" "If you recognize that you may lose your balance, bend your knees to recover" "If you need to stop your walking quickly, try to include balance recovery strategies like bending your knees"
I3 Task-switching strategies	"If you recognize that you may lose your balance due to added tasks, focus your attention on your balance or walking performance" "If you have concerns about falling, try to stay relaxed and bend your knees a bit to reduce muscle stiffness"
I4 Task prioritization strategies	"If you are engaged in a difficult secondary task, try to find a task prioritization solution (e.g., if you need to look up at a sign to find your way, try to stop and slow down, view the sign, and continue walking afterward)" "If you are engaged in a difficult secondary task, try to switch between the cognitive and the motor component to stay aware of your walking or balance performance" "If you need to do a brisk walking task, try to remember your foot rolling movements" "If you are engaged in a situation with many people around you (e.g., at a train station), try to focus on your own movements and balance control strategies when someone bumps into your shoulder"

Note: I = instruction

specific or a general training regime (e.g., Tait et al. 2017). Based on such knowledge, we would be able to design training protocols which will allow us to systematically achieve defined training goals. However, as we tried to point out, effectiveness is modulated by many factors like the temporal scheduling, the training dose, the momentary functional capacity of the system, etc. Things are complicated even further by the fact that these factors are nonlinearly linked in a yet not well-understood way, with this interrelation being potentially different for different targeted subsystems.

In the following, we will give an integrated overview of what is known so far about the efficacy of different combined simultaneous cognitive-motor training regimes. The contents of these interventions are connected to dual-task training regimes. We classified four categories of training settings, allowing us to group existing research in a sufficiently coherent way (cf. Fig. 1).

The categories we use mainly differ in the degree to which the targeted processes or performance effects are specific to the actual set of trained tasks. Along that dimension, we will look at *specific cognitive-motor training* settings, at *general* *cognitive-motor training,* and at *task management training* (Wollesen and Voelcker-Rehage 2014). As a fourth category, we will separately look at *virtual immersive training* settings. The latter do not necessarily differ along the specificity dimension; nevertheless, they deserve a separate presentation here for reasons explained below.

Specific Cognitive-Motor Training (SCMT)
A *specific cognitive-motor multitasking training* targets a change in performance in the *practiced* task combination, which could be affected by an improvement in one of the crucial sub-processes of the specific task combination. It integrates the specific subtasks of the training goal and might follow a specific training protocol (including, e.g., progression of intensity or task complexity, cf. Doumas et al. 2009).

General Cognitive-Motor Training (GCMT)
A *general cognitive-motor multitasking training* aims to improve the capacity of a latent factor or a general processing capacity that is crucial in a number of different tasks. To achieve this goal, a variety of different task combinations involving this latent factor is practiced. Any increase in the capacity of the underlying processes will then be visible as an increase in either ST or multitasking performance even in untrained tasks, which is also called *far transfer* (Karbach and Kray 2021; for more detailed descriptions of transfer types, see Karbach & Strohbach, this handbook). Examples are a complex cognitive-motor coordination training or other exercise types that demand the execution of more than one task (component) and a high level of coordinative abilities often integrated in falls prevention programs of older adults (cf. Wollesen and Voelcker-Rehage 2014).

Task-Managing Cognitive-Motor Training (TCMT)
A *task-managing cognitive-motor training* intends to improve skills in dealing with requirements that generalize across different multitasking combinations. In contrast to specific training, strategies of task switching or task prioritization are explicit parts of the training and are integrated in the instructions during the exercises. The underlying idea is that certain aspects like a properly scheduled allocation of

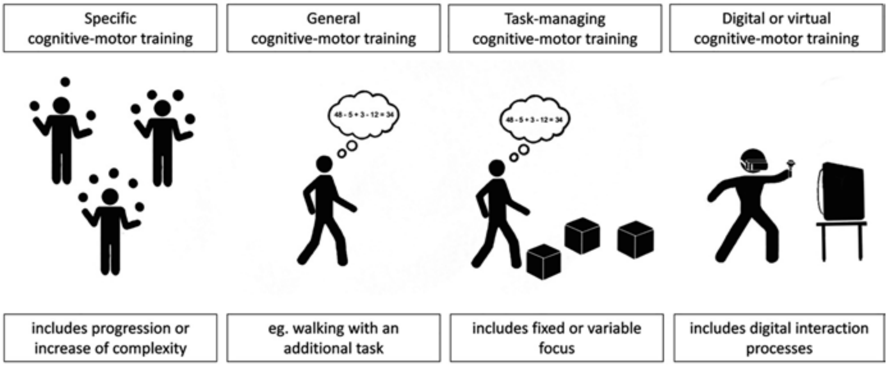

Fig. 1 Different types of cognitive-motor multitasking training

resources, the inhibition of unwanted responses, or the switching of task sets can be trained and that improved capacities can then be transferred to other task combinations. Moreover, especially in older adults or for specific working conditions (e.g., air traffic controller), task-managing strategies can also address task switching (cf. Wollesen et al. 2015, 2017a, b, 2018), task prioritization (e.g., fixed or variable focus of attention, cf. Lussier et al. 2017), or multiplexing (flexibility and efficiency of representation, managing of cross-talk, cf. Feng et al. 2014).

Digital or Virtual Cognitive-Motor Training (DCMT)
Many commercially available training programs try to immerse trainees in an appealing virtual environment with game-like tasks, so-called *exergames* (Anderson-Hanley et al. 2017). Exergaming combines physical and cognitive exercise in an interactive digital, augmented, or virtual game-like environment. Many of those video games can be classified as cognitive-motor multitasking training because they integrate motor and cognitive demands simultaneously (Pichierri et al. 2011; Monteiro-Junior et al. 2016). It is often difficult to discuss these scenarios regarding their actual intention in the sense of our three categories so far. It is not always clear which effects are actually intended. Despite the fact that many of these games have different difficulty levels and are, in principle, adaptive to the performance improvements, the adherence to the training principles mentioned above is far from being strict. Many of these training tools are designed for home-use, which is in part a big advantage, as participants can train independently without travelling to a gym or time restrictions of organized training sessions. However, the actual training dose, the scheduling of the training episodes, and the compliance of subjects are often not well controlled, making any comparison to other programs difficult. In the following paragraph, we will therefore discuss studies in that field in a separate section.

3.3 Aims of Cognitive-Motor Multitasking Training (CMT)

As mentioned above, training is applied in order to enhance a targeted processing component with the final goal to improve its functional capacity. This, however, can be conducted at different starting levels of expertise and different aspired performance levels. Therefore, with respect to research in exercise science, we will address three main areas of goal-directed training intervention in this chapter: (1) motor learning and skill acquisition, (2) performance optimization, and (3) preservation of resources. Training interventions pursuing these aims can address different target groups and result in improvements of cognitive, motor, or cognitive-motor dual-task or multitasking performance in different daily life or sport settings.

3.3.1 CMT to Improve Motor Learning and Skill Acquisition

The domain of learning and skill acquisition addresses mainly the question, how new and complex multitasking situations can be managed by novices or how automatization can be reached in activities of daily living (ADLs) or when learning to combine specific team sports skills and tactical elements.

To illustrate the main aspects that potentially need to be focused on in a multitasking training intervention trying to improve skill acquisition, we may look at the example of learning to drive a car. This may represent a whole class of comparable navigation tasks involving simultaneous control of sufficiently complex motor activities and environment-related decisions on pace and heading direction. Other examples could be navigating through a crowded bazaar while picking up price information or dribbling through a group of opponents while looking for passing opportunities.

If we recall our first attempts in driving a car, we may still remember the multitude of subtasks that somehow needed to be integrated: delicate hand (steering) and foot (pedals) movements, gaze control (mirror) while information from all modalities (visual [distance to curb], acoustic [revolution speed of motor], vestibular [centrifugal forces], etc.) rush in almost simultaneously. Moreover, successful movement execution requires the perceptual and motor resources to deal with unforeseen changes in the environment. An isolated learning of each component separately is only possible when the environment is standardized and controlled like in a simulator training. To prepare for the real-world task, however, it might be helpful to integrate multitasking training (e.g., with task prioritization and task switching or guided attentional focus) to better control the interaction processes of the different subcomponents, to stabilize performance even in the presence of distractors.

Whereas it might look straightforward to naively name potentially relevant subtasks for the driving example, in which we all have at least some experience, it might turn out to be more difficult to identify the main aspects that need to be focused on in a multitasking training intervention for other tasks. In these cases, it might therefore be helpful to try to describe the to-be-learned sports or daily life skill by means of a storyboard, analogue to the example of cooking a dish by Salvucci and Taatgen (2008). Following this idea, the relevant subtasks could be disentangled and may become more visible, and an adequate training composition can be designed on that basis. The resulting storyboard and timeline for an exemplary motor-skill might look as follows (cf. Table 4):

In this example, we assume hitting the ball as the primary task. This task needs procedural resources for the movement execution with the control of foot placement, body orientation, timing, speed, and direction of arm movement. Tactical knowledge and prior experience allow an informed guess which ball placement promises highest probability of success. Moreover, both tasks, the tactical decision and movement control, require that certain activities (e.g., gaze control) secure the required perceptual input. As long as there is no distraction from the environment, the movement execution may be learned by focusing on each particular phase (jumping, arm movements, landing) separately. Eventually, the complete dual-task

Table 4 Example of describing control processes while executing a volleyball spike as means to identify deficient sub-processes as targets for training interventions

TIMELINE	Motor performance (primary task) goal	Secondary task (tactical decision)	Control perceptual input (information processing and updating)
↓	*Hitting the ball in the air at the highest point to smash it over the net*	*Decide where to place the smash*	*Observing ground, ball flight, and position of opponent*
	Execute the jumping – Control of foot placement Execute the arm movements – Control of speed – Control of direction – Control the second arm Execute the landing – Control of foot placement	Predict positions of block Identify “open areas“ Spot weakest defender	Observe ground floor conditions at jump and landing position (wet, slippery, obstacles…) Observe the ball Observe other team members …

may become automatic after many repetitions with the according feedback. For the learner, it might nevertheless be helpful to integrate multitasking training (e.g., with task prioritization and task switching or guided attentional focus) to better deal with task interactions in different movement phases, particularly in case of distractions, such as noise, visual occlusions, or unexpected movements of other players.

With increasing task experience, performers identify the specific functional performance information (e.g., the time needed to decelerate to a desired tempo in the car driving example or position of opponents in the volleyball example). Training or practice helps the learner to focus on such relevant information and to inhibit irrelevant signals. The process of calibration includes the scaling of the perceptual-motor requirements to changing task requirements (e.g., different cars, different balls) and variation in individual capabilities (e.g., driving when being tired, jumping while being exhausted). Moreover, in sports, experienced athletes are able to integrate information scaled to the action capabilities of others (e.g., teammates or opponents in sport) and to adapt their own motor responses (Davids et al. 2012). A secondary cognitive task affects the processing mode of a primary motor task and thus changes information processing related to motor learning. It inhibits explicit processing in favor of implicit processes (Patel et al. 2014). Therefore, this kind of intervention might be beneficial for adaptive motor learning with benefits for rehabilitation interventions as well (Patel et al. 2014).

The domain of learning and skill acquisition addresses mainly situations in which persons learn to manage new and complex multitasking situations. Building on existing basic skills, performers have to learn and adjust to different aspects of the new task (combination): (a) they have to develop a suitable set of intentions and subgoals (which number of possible perceptions and action goals should be realized?), (b) identify relevant information components and direct attention to them (which information needs to be focused?), and (c) adapt and calibrate input and output parameters (adjustment of information to one's action capabilities; Davids et al. 2013). These components are relevant across different situations, tasks, and variations in personal factors, ranging from activities of daily routine to leisure sport, but also professional work.

Despite the fact that the acquired skill should be robust across a variety of different situations, the typical multitask training to develop these skills can be classified as specific cognitive-motor training, in some cases also involving task-managing cognitive-motor training. All principles and instructional strategies mentioned in Sect. 3.1 should be applicable. Yet, one would expect performance increase, even when these are not followed strictly, though improvements might not be optimal.

3.3.2 CMT for Performance Optimization (Automatization)

Performance optimization in the field of human movement and sports science refers to a situation where learners that have already reached a reasonable level of expertise are now either striving to push their performance to the maximum or are trying to minimize the effort when operating at a given level. Adapted to our context here, this refers, for example, to cases where individuals have already learned relevant cognitive-motor skills but are now trying to keep their performance stable in competitions as well or situations with a high stress level. Therefore, multitasking training to optimize performance will mainly address adults on a certain level of working expertise or sports experience as well as (elite) professional musicians.

For a more complex task like attacking the goal in a professional ice hockey match, a lot of different actions or subtasks need to be processed. Successful operation in an ice hockey match requires handling a large number of subtasks under substantial time pressure. In addition, the player might experience stress or pressure because failure may cause championship loss. Under these conditions, the best performance may only be possible, if all subroutines run automatically without suffering from interference with other subtasks and (slow) central cognitive processes contemplating on possible strategies.

As implied by the examples presented so far, training for performance optimization often targets automatization. In this case, a specific dual-task training, where particularly the involved components and subtasks are practiced, might be highly relevant. In order to reach the optimal results, all training principles should be followed as strictly as possible. It is particularly important to secure an optimal training intensity that is adjusted to the performance level of the trainee. Since performance increments will eventually level off when the ceiling is reached, optimal intensity might not change too much. Nevertheless, particularly in those situations, principles P6 (periodization) and P7 (variability) require sufficient attention.

3.3.3 CMT for Preservation and Relocation of Resources

With advancing age or related to specific health issues, routine actions in everyday life, such as walking, driving, or typing on a computer keyboard, require more cognitive control and attentional resources. Also walking in our natural environment can be considered a dual-task scenario that requires increasing cognitive resources with increasing age (Poole et al. 2019).

Therefore, a simple street crossing task might become a big challenge if an older adult has to cross a busy street at a traffic light. Managing the situation requires timely and sufficiently accurate motor control while walking and sufficient processing speed to deal with the time pressure induced by the traffic lights and the continuous observation of traffic flow.

This example may only be adequately captured by a very complex storyboard (according to Salvucci and Taatgen 2008). Overall, the situation might result in problems of movement execution for older adults. As mentioned above, one problem of continuous cognitive-motor interference results from the fact that the task cannot be interrupted at a certain stage (the moment when the older adult started to walk across the street). This situation might even become more challenging if the older adult has concerns that they might not be able to cross the street within the time of the green phase of the traffic lights and if these concerns affect resource allocation, especially if attentional processes are involved. In older adults, brain networks dedifferentiate and the brain undergoes functional and structural changes (Rajah and D'Esposito 2005; Fjell and Walhovd 2010; Corp et al. 2016), while selective attention declines. Similar to children, older adults are less able to focus attention on task-relevant information and to inhibit task-irrelevant information from simultaneous and competing information streams (Korsch et al. 2014; Reuter-Lorenz and Lustig 2017), especially during visual stimulation. During multitasking, older adults might overprocess interrupting stimuli and have problems to reactivate information following interruptions. Accordingly, Clapp et al. (2011) conclude that older adults have problems with disengagement of the distractor. Age-related decreases of dual-task performance were also identified for task switching (Wasylyshyn et al. 2011), memory updating (Bopp and Verhaeghen 2005), and response inhibition (West and Alain 2000). Moreover, the efficiency and capacity of older individuals' cognitive networks may differ. Cabeza (2002) and Stern (2009) described the cognitive reserve model that focuses on functionality, plasticity, and adaptability of the brain, which are influenced by all aspects of life experience (Stern 2009). Thus, the cognitive reserve model can give explanations why some people can better cope with age- or pathology-related brain changes than others, depending on their cognitive reserve capabilities. However, these mechanisms are also true for sports-related cognitive-motor aspects or resource allocation.

Moreover, physical and motor fitness are related to cognitive performance and in turn might affect multitasking performance in older individuals (Voelcker-Rehage et al. 2010). Regarding cognitive-motor interactions, Schaefer and Schumacher (2011) summarized that elderly people tend to prioritize motor ability over cognitive tasks when balance is threatened. This was discussed as older adults prioritizing walking over memorizing to protect themselves from falls, a view known as "*posture first hypothesis*" (Shumway-Cook and Woollacott 2000; Schaefer and Schumacher 2011; cf. Li et al. 2012, for discussion of mixed results). Moreover, the combination of high-risk task settings (e.g., elevated surface) lead to problems of task prioritization in healthy older adults as well (Schaefer et al. 2015). When fallers are compared to non-fallers, they show a scaled-down balance performance in DT which is indicative of reduced ability in EF and the focus to prioritize gait (Springer et al. 2006). Finally, many older adults have problems in shifting attention to postural control due to concerns about or fear of falling. The review of Young and Williams (2015) found that a concern of falling (CoF) interferes with attentional resources and the ability to appropriately acquire sensory information and therefore may impair gait in general. People with higher levels of CoF have difficulties to inhibit or ignore irrelevant information of the environment in the process of balance control (Young and Williams 2015). Additionally, cognitive-motor interference rises with increasing task complexity and according to the individual abilities and resources (Lacour et al. 2008; Wollesen et al. 2016).

Training for preservation of resource can target the different aspects of cognitive-motor interference or decrements in older adults: (1) It may reduce age-related motor or cognitive declines in general. (2) It can improve executive control required to deal with different task complexities. (3) It may include training with realistic daily life scenarios of task complexity of the motor task (e.g., walking situations). (4) This type of training may also address task-managing strategies (e.g., of task prioritization; posture first). (5) It allows to deal with previous falls or concerns of falling. Most of these aspects are also relevant for other target groups that might have reduced resources, e.g., due to chronic diseases. Regarding these different aspects, all types of multitasking training might gain benefits, when improving parts of these targets, especially if they integrate the principles P1–P7 as well as tailored instructions for task-managing strategies I1–I4.

4 Empirical Evidence for Effectiveness of Cognitive-Motor Multitasking Training (CMT)

In this section, we will systematically review empirical studies in which the effects of cognitive-motor dual- or multitask training have been studied. We will structure this review according the four basic types of cognitive-motor multitasking training described in Sect. 3.2. In each of these four subsections, we will also look at different target groups, each with its own specific needs. Reliable improvements through systematic training are particularly desired in populations where performance is limited for some reason or where well-learned and automated processes are a prerequisite for success such, as in sports or in certain work contexts (e.g., pilots). Accordingly, a huge body of literature has investigated practice and training effects in older persons and in clinical populations, whereas comparatively few studies on children or athletes exist so far. However, multitasking training interventions might also be beneficial for athletes or training for different kinds of sports in general or for children and adolescents when they learn new motor skills. In different kinds of team sports (e.g., soccer, volleyball, basketball), there are many situations where different cognitive and motor processes have to be executed at the same time.

Therefore, all sections within this chapter will give an overview of relevant results on effects of interventions related to the target groups of children and adolescents (young adults), adults, athletes, older adults, and patients. The presented results of benefits of CMT integrate randomized controlled trials or quasi-experimental studies with active or inactive control groups.

All examples of multitasking situations for different target groups presented here have in common that the primary motor task is executed continuously with an ongoing information processing and updating of information on environmental conditions.

4.1 Results of Specific Cognitive-Motor Training Interventions (SCMT)

The main body of studies for SCMT integrates specific experimental setups and controlled amounts of training activity where a certain motor task (such as balancing) is practiced in combination with a secondary task. In comparison to the other forms of multitasking training, the number of studies is still limited. The training interventions mainly focus on balance performance in DT situations. Moreover, some studies with athletes in ball sports exist. To evaluate training efficiency, effects of specific DT training are often tested against single-task training.

Children and Adolescents SCMT studies with children or adolescents are rare. A training with adolescents (12–16 years) combining balance training (center of pressure disturbances) with a backward digit span test revealed a better DT-task balance performance in comparison to the training of both elements separately (Bustillo-Casero et al. 2019). Another study showed that, while learning a mirror drawing task, a cognitive secondary task affected the performance of ten-year-old children but not seven-year-olds. This is interpreted as an indication for higher explicit involvement in learning in older than younger children as the learning rates were identical (Lejeune et al. 2015).

Adults SCMT balance training studies have also been conducted with young adults. Kiss et al. (2018) examined the effect of seven 90-second practice trials on a moving platform under ST and DT task training conditions (counting backwards in threes). As a main result, the authors reported that the DT balancing performance showed higher improvement if tasks were trained simultaneously (for similar results, cf. Pellecchia 2005) with three sessions of practice. SCMT has been shown to be also successful to improve multitasking walking performance in young adults (avoiding obstacles while performing an auditory Stroop task; Worden and Vallis 2014). A study by Kimura and Matsuura (2020) examined an additional cognitive training of auditory stimuli responses to knee-extension force modulation combined with n-back performance simultaneously. The multitasking group (knee-extension plus two cognitive tasks; n-back and auditory task) decreased dual-task costs to a higher amount in comparison to the DT group (knee-extension plus auditory task). Some studies, however, revealed similar effects of ST and SCMT training (Kimura et al. 2017; force modulation of an upper and lower limb task in combination with a visual manual choice reaction task). As both studies are conducted in an experimental setup with different cognitive complexities of the task sets, the transfer into real-life settings needs to be questioned.

Athletes Studies targeting athletes are rare. A four-week progressive DT-task training in healthy physical recreational athletes (with increasing complexity starting with e.g., counting backwards and ending up with WII-balance tasks with catching and other motor reactions), conducting different complexities of mono- and bipedal standing situations, did not lead to better performance in a transfer to an attentional test battery compared to a training that integrated both training approaches separately (Ingriselli et al. 2014).

Older Adults For older adults, most of the SCMT interventions were conducted to improve cognitive-motor performance for daily situations like standing or walking. Only few training interventions address upper extremity tasks such as driving or fine-motor control (cf. McDowd 1986; Shinar et al. 2005).

Specific training interventions addressing balance performance (center of pressure –displacements) with additional cognitive tasks led to positive effects on cognitive performance for a visual–verbal visuospatial task (Dault and Frank 2004) and decreased DT costs (executive n-back task, Doumas et al. 2009). Additionally, Doumas et al. (2009) reported improvements for older and younger adults to compensate centre of pressure (COP) on a fixed or moving platform (reduced COP displacements) while performing an executive visual–verbal n-back task (executive control) after a specific DT training. You et al. (2009) as well as Ansai et al. (2017) found improvements for the cognitive task (working memory task) under DT walking conditions.

McDowd (1986) compared practice effects in young and older adults by use of a perceptual-motor task (six 1-hr sessions). Absolute levels of performance improved over sessions for both young and old participants, but divided attention performance remained poorer in old than in young adults. Shinar et al. (2005) compared young, middle-aged, and old adults in practicing a DT driving task (carrying out two different "phone" tasks, five sessions) and found a learning effect on driving. In addition, the interference from the phone task was larger when the driving demands were larger and when the drivers were older, but DT costs diminished over time.

Patients The positive effects of SCMT on walking performance were also confirmed for participants with brain injuries and with Parkinson's disease (cf. review

Fritz et al. 2015) or other neurological disorders (stroke, multiple sclerosis, mild cognitive impairment (MCI), dementia; Kim et al. 2014; Lemke et al. 2019; Hagovská and Olekszyová 2016) as well as in nursing home settings (Rezola-Pardo et al. 2019).

The main duration of programs for older adults and patients was six up to 16 weeks, with mostly two 45–60 minutes sessions per week. Many of these interventions for older adults and in therapy settings include aspects of individualization and progression. A main advantage for the therapeutic setting of this kind of DT training is that it addresses individual decrements, e.g., decrements in complex ADLs can be addressed systematically depending on a patients' problem (e.g., foot placement while walking, avoiding obstacles, fine motor tuning/force control, etc.). Although there is evidence that the simultaneous cognitive-motor training is more effective than practicing both components separately (Kim et al. 2014), there might also be disadvantages of simultaneous training regimes. This applies particularly to groups with a low performance level. For example, within a learning procedure of a walking pattern on a split belt treadmill, the influence of a secondary cognitive task led to general slowing down of the learning process of older adults in comparison to younger adults. Moreover, the older adults forgot more aspects of the new walking pattern within the given breaks of the learning phases (Malone and Bastian 2016). Therefore, the conduction of interventions requires to integrate the individuals' responses and abilities to adapt to the given task settings.

Summary SCMT

Besides the fields of older adults and for neurological disorders, this kind of training was also conducted to improve cognitive-motor performance of children, adults, and athletes for motor skill acquisition or working performance. This training has the potential to improve motor, cognitive, and cognitive-motor performance. The main examined outcomes for all target groups were balance, walking with additional tasks (e.g., obstacles), fine motor (precision) tasks, force modulation, and driving. Studies with athletes integrated sports-specific movements like catching a ball.

With respect to the specificity of these interventions, even a short duration of the training period can produce positive effects. The different target groups already benefited from the interventions if the duration was four weeks with a frequency of three sessions. The aspects of specificity allow to integrate individualization of training complexity and load as well as progression.

4.2 Results on General Cognitive-Motor Training Interventions (GCMT)

Studies regarding GCMT are mainly conducted for older adults or within therapy settings. Most of these studies integrate the assumption that a general combination of cognitive-motor interaction might free up general resources for cognitive and/or motor performance. Fewer studies also focused on children and adolescents as well as athletes or adults, either addressing general motor and cognitive outcomes or balance.

Children and Adolescents Within the variety of exercise intervention literature, one study examined the effects of GCMT including fine and gross motor body coordination, balance, hand-eye coordination, spatial orientation, and reaction to persons and objects, on different cognitive and motor outcomes in children (aged 8–10 years; Koutsandreou et al. 2016). The described intervention was compared with aerobic exercise and an inactive control group. While the training groups both improved physical fitness and cognitive performance, additional statistical analyses revealed advantages for the GMCT group in improvement of working memory performance. Another study compared a ST balance training to a DT balance training (integrating simple working memory tasks and manual tasks and a progression of balance performance) within school children aged 12 to 13 years (for eight weeks, 20–30 min in regular physical activity classes): The results showed that both interventions improved performance for standing balance and walking while counting backwards in threes. However, the test situation might have been not challenging enough to induce clear DT decrements (Lüder et al. 2018).

Adults A four-week motor-cognitive DT training conducted as workplace health promotion following the life kinetic concept (Niederer et al. 2019) in comparison to an inactive control group was not suitable to increase cognitive (d2-test, Trail Making Test) or motor performance (lower-body choice reaction test and time to stabilization test). This concept was also successful within an eight-session program in comparison to endurance training within the study by Johann et al. (2016). Within this study, the authors compared the impact of this intervention on physically active and sedentary participants as well as to an inactive control group. While both training interventions increased the cognitive and motor abilities of the participants, the cognitive-motor training was more beneficial in comparison to the cardiovascular training for the sedentary group and more successful to transfer motor abilities into an unknown coordination task.

Athletes Within a study regarding the DT abilities of rugby players, the authors examined an eight-week training of passing and drawing the ball with counting backwards (Gabbett et al. 2011) in comparison to a ST passing and drawing training. The authors observed benefits for the DT group for the test situation including passing and drawing the ball with a tone recognition task; however, as both groups improved their performance, the interaction effect failed to be significant (Gabbett et al. 2011). This leads to the idea that a transfer of DT abilities from counting backwards during passing and drawing a ball into tone recognition cannot be revealed with this kind of DT training.

Older Adults Studies on older adults and patients clearly predominate. GCMT for older adults mainly includes a variety of DT situations in combination with balance or walking performance. Most training interventions were conducted to support falls prevention programs as well as to provide suitable training for remaining resources for ADLs. Many interventions (Hiyamizu et al. 2012; Toulotte et al. 2006; Trombetti et al. 2011; Westlake and Culham 2007) performed a general balance or fall prevention program including balance, strength, and walking tasks combined with different cognitive tasks like reciting poems, calculating numbers, or visual-spatial tasks, cognitive music tasks (e.g., react on rhythmic changes), letter counting tasks, or executive control tasks like variations of the Stroop task. The GCMT interventions aiming to improve static and dynamic balance performance (standing and walking) were successful to improve standing or cognitive performance. Mostly, the abilities to control the base of support were investigated, and reduced postural sway was regarded as an indicator of training benefits.

Improved walking performance is associated with increased walking speed (with accompanying spatiotemporal parameters like step length, double-support time, etc.), reduced gait variability, or improved abilities to do a narrow walk or avoid obstacles (Wollesen and Voelcker-Rehage 2014; Azadian et al. 2016; Maclean et al. 2014). Unfortunately, not all included studies reported the cognitive and the motor DT costs (Wollesen and Voelcker-Rehage 2014). Other studies on older adults focused on cognitive performance as the main outcome variable, such as the trail making task (Hiyamizu et al. 2012), working memory (Azadian et al. 2016; Nishiguchi et al. 2015), visual reaction and spatial awareness (Fragala et al. 2014), or executive control tasks (Hiyamizu et al. 2012; Theil et al. 2013). Yet others investigated specifically the effects of a GCMT on abilities associated with driving performance (visual attention, psychomotoric performance, speed perception, executive functioning; Marmeleira et al. 2009) or the speed of behavior during on-the-road driving (three sessions of 60 min/week for 8 weeks; Marmeleira et al. 2011). Significant positive effects were found for driving tasks.

First studies on GCMT (one hour training, three times per week over 12 weeks) tried to verify the observed behavioral changes with neurophysiological correlates (e.g., Yokoyama et al. 2015). So far two studies have been conducted investigating biomarkers of Alzheimer's disease, with contradictory results, Yokoyama et al. (2015) failed to reveal changes on plasma amyloid ß peptide (Aß) 42:40 ratio due to GCMT (Yokoyama et al. 2015). Lee and Nam (2020) applied a comparable training, but with a shorter duration (30 minutes three times a week for eight weeks) and revealed a decrease of the overall ß-amyloid level in participants with mild cognitive impairments (Lee and Nam 2020). Also, effects on cortical thickness in different parts of the left and the right hemisphere along with improved balance performance have been shown after a GCMT (Rogge et al. 2018).

Patients GCMT was also found to be a useful training regime for different neurological diseases, including patients with MCI or dementia, especially to improve walking performance under ST and DT conditions. The training regimes are often conducted as multimodal programs including aerobic, strength, and balance exercises combined with different cognitive (naming animals, counting backward, memorizing word lists) or motor tasks (e.g., reaction to balls or catch/throwing balls; Gregory et al. 2015, 2017; Makizako et al. 2015; Schwenk et al. 2010). The duration of successful multimodal interventions was 12–26 weeks with two training sessions per week. In addition, aerobic training combined with different kinds of cognitive tasks (24 weeks) improved cognitive and physical function (Park et al. 2019). Moreover, eight weeks of combined music and walking training improved attention control, falls efficacy, and agitation in their group of patients (Chen and Pei 2018).

Comparable results have also been shown for patients with Parkinson's disease. Multimodal or walking and balance GCMT interventions improved mainly ST and DT walking performance as well as cognitive performance in different domains (Beck et al. 2018; Löfgren et al. 2019; Penko et al. 2019; Rosenfeldt et al. 2019; Wallen et al. 2018). These interventions were offered three times per week for at least eight weeks. Moreover, it needs to be addressed that according to the results of Wallen et al. (2018), the positive effects deteriorate if the training was not sustainably continued.

Summary GCMT
General cognitive-motor training interventions were mainly evaluated in the fields of older adults and for neurological disorders. It was shown that this training, mostly including different balance, coordination, and walking tasks, has the potential to improve motor performance (balance, walking, driving) under ST and DT conditions. Also, cognitive performance can benefit from these interventions with accompanying neurophysiological correlates. The duration should be at least eight weeks with a frequency of two times per week. In cases where the cognitive-motor decrements are presumably due to neurological diseases, the number of sessions needs to be increased.

Moreover, within some studies, only ST cognitive or motor performance was improved. This suggests that the composition of the different training tasks might play an important role to which extent multitasking performance is facilitated in different target groups. Nevertheless, it remains unclear how the general performance components respond to training. Parameters of training control and adjustment of training load are often not reported. However, a suitable determination of training loads might be instrumental to gain higher improvements in cognitive, motor, as well as cognitive-motor performance.

4.3 Results of Task-Managing Training Interventions (TMMT)

The main characteristic of TMMT is the combination of exercises with instructions that will guide the focus to different aspects of the sub-processes that are relevant to build up strategies, for example, for motor control in balance demanding situations. The explicit instructions aim to guide the resource allocation and therefore to help the participants to find solutions for motor or cognitive control. As these strategies are highly relevant in falls prevention or for persons with decreasing cognitive abilities, most of the studies that examined TMMT focused on older adults or patients; studies with other samples are missing.

Older Adults A few TMMT studies were conducted to support older adults' abilities or performance for ADLs. The main idea of these interventions is that there is an instructional guidance through task prioritization and/or task switching and corresponding cognitive or motor strategies. First studies, for example, Bherer et al. (2005), used training paradigms with a fixed or variable focus of attention. They were able to show improvements for conflicting simultaneous DT motor responses in younger and older adults (Bherer et al. 2005).

In line with these results, motor training, including different foci of attention, improved cognitive performance (auditory verbal counting backwards task; controlled processing; Silsupadol et al. 2009a). In addition, Silsupadol et al. (2009a, b) found improvements in a task requiring controlled processing while walking. Moreover, studies of Wollesen et al. (2015, 2017a, b, 2018) including the training of task switching and task prioritization together with a progression of training load and task complexity found positive effects on gait performance under ST and DT conditions (visual–verbal Stroop task). In comparison to a strength training group, some participants of the TMMT reported that they changed their -managing strategy from prioritizing the cognitive task to focus on both tasks equally (Wollesen et al. 2018). This strategy change did not result in performance decrements of the cognitive task but in improvements of the walking performance (Wollesen et al. 2018).

Patients Currently, the positive contents of these TMMT have been adopted for use in multicomponent training intervention with nursing home residents (Bischoff et al. 2021), participants with hearing impairments (Wollesen et al. 2021a), patients with Parkinson's disease (Wollesen et al. 2021b; Brauer et al. 2011), and dementia (Perumal et al. 2017). Moreover, positive results were found on DT gait performance for participants with stroke, if the DT training was performed with variable focus strategies (Sengar et al. 2019). Most of these interventions integrated 12 to 24 sessions with a duration of 30–60 minutes to gain positive effects.

Summary TMMT

The main examined target groups of these interventions are older adults and neurological patients. This type of training intervention seems to have great potential to improve cognitive-motor performance and relevant strategies to manage complex cognitive-motor situations. The main outcomes examined in the reported studies were dual- or multitasking balance or walking tasks. The duration of the training was reported with at least 12 sessions. Within these sessions, individualization and progression of training load and task complexity were helpful to increase cognitive-motor performance. An accompanying education of task-managing strategies might be a good opportunity to gain a larger transfer into daily activities and long-term effects.

4.4 Results of Digital, Exergaming, or Virtual Cognitive-Motor Interventions (DCMT)

Virtual reality setups are used to create controlled environments where subjects ambulate while being confronted with additional tasks like wayfinding, obstacle avoidance, event counting, or other cognitive tasks. Subjects typically improve their performance in the practiced motor task and the cognitive task. Typically, a cognitive task was either explicitly added or was considered to be already part of the natural situation (counting steps, adjusting to the music beat, etc.). These interventions are well described for children, adolescents, and older adults.

Children and Adolescents Digital or virtual interventions are proven to be a motivational alternative to increase physical activity in children and adolescents (Lwin and Malik 2014; Fogel et al. 2010). The digital or virtual surrounding incorporates video gaming consoles like PlayStation, Xbox-connect (Kinect adventure), and Nintendo Wii. Many of these interventions used dancing games but also games like Sport Rival & Boom Ball and Shape Up were played. All games have in common that the players must control the game by using bodily movements (e.g., with controllers including motion control).

Next to motivational outcomes, these interventions have been used to improve motor fitness and support motor skill learning. For example, Bonney et al. (2017) examined 111 children aged 6 to 10 years with and without developmental coordination disorders (DCD). They played Nintendo Wii Fit Games for 20 min two times a week (six weeks) randomly assigned to two training regimes: (1) variable gaming and (2) scheduled practice. The main goal was to improve balance abilities. In summary, all children were able to improve their balance abilities independent of the training regime (Bonney et al. 2017). A comparable study with the same training duration and target groups (N = 36) found balance and agility improvements for both groups, however, with advantages for the children with DCD (Smits-Engelsman et al. 2017). These improvements on balance performance were also found for third-grade children using the Wii fitness program (three times a week for six weeks; Sheehan and Katz 2012). However, a non-exergame training group receiving special balance and coordination training showed the same positive effects, whereas the control group following their usual physical activity routines did not increase their performance (Sheehan and Katz 2012).

Vernadakis et al. (2015) examined the effects of eight weeks (two times a week for 30 minutes) of Xbox Kinect mini games (baseball, bowling, soccer, and NBA baller beats) on fundamental motor skills like striking or dribbling, catching, overhand throwing, underhand rolling, and kicking a ball in six- to seven-year-old children. The training intervention was compared to the same dose of traditional exercises for developing these motor abilities and a group of children without training. In contrast to the control group, both training interventions showed the same positive effects on the ball handling skills of the participants.

Regarding cognitive performance, a study by Gao (2013) revealed that Dance Revolution-based exercises improved math scores. This effect was accompanied by significant improvements of the cardiorespiratory fitness, and therefore it remains unclear if the improvements are a result of general motor fitness effects, for example, on executive processes or resource allocation, or if the multitasking setting helped to improve cognitive processes to solve arithmetic tasks. In addition, a study by Benzing et al. (2016) examined male adolescents (13–16 years) during exergaming at high and low levels of cognitive engagement. The results showed that cognitive performance improved most for the high-level cognitive engagement group. They showed better performance in cognitive flexibility (Benzing et al. 2016). Nevertheless, this group had a greater heart rate variability during the exergames compared to the low-level cognitive engagement group while running.

Moreover, the application of three different exergames including balance shifting as well as inhibition control (Sport Rival & Boom Ball and Shape up; 30 min three times a week) improved the eye-hand coordination in the adopted mirror tracing task of children aged 11–13 years (Ma and Qu 2016).

Adults For adults, a virtual reality (VR) training often integrates driving abilities or tracking of tasks in different environments. These studies mostly integrate a fine motor task of aspects of multiple object tracking.

Observing driving abilities, the study by Isler et al. (2011) revealed positive effects on driving performance of young drivers (age 18–19 years) after a simulated driving training including verbal responses to distractors. Improvements of the accuracy for a lane change task combined with a visual search task or a tracking task were found by Huemer and Vollrath (2012) after DT training. However, the authors recommended the training of the ST conditions before adding the DT scenarios (Huemer and Vollrath 2012).

Moreover, balance performance and safety aspects were addressed in VR environments. The study by Cyma-Wejchenig et al. (2020) examined VR training on a balancing platform together with arithmetic tasks (12 sessions) with improvements on balance performance in ST and DT conditions. The same positive effects on trunk velocity were found by Hara et al. (2018) with a VR training including reaching toward objects (96 trials with a duration of one to five seconds; Hara et al. 2018).

Athletes For athletes, a visual-motor stroboscopic training (eight sessions with 30 min of training) was beneficial to improve divided attention and multiple object tracking in football and frisbee players (Appelbaum et al. 2011).

Older Adults A variety of the described exergames have been used to improve cognitive-motor performance in older adults. For example, addressing balance performance, two studies (Bisson et al. 2007; Lajoie 2004) used VR games as a DT biofeedback training. Bisson et al. (2007) asked their participants to juggle a virtual ball with additional real-time visual feedback (two sessions of 60 min/week, 8 weeks), and Lajoie (2004) used a virtual tennis game (two sessions of 30 min/week, 8 weeks). In both studies, participants were asked to compensate their center of pressure displacements simultaneously, i.e., while observing a virtual ball and using arm movements to hit the ball. Two recent reviews (Stojan and Voelcker-Rehage 2019; Wollesen et al. 2020) reported that the most frequently utilized type of exergame systems among their included studies were dance and step video games.

The meta-analysis by Wollesen et al. (2020) showed that most of the exergaming interventions were able to increase processing speed during reaction time tests. Moreover, a variety of studies examined the effects on different other cognitive functions, for example, executive functions, as well as short-term memory, and controlled processes (cf. Stojan and Voelcker-Rehage 2019). Some of these studies integrate individualization aspects, for instance, assessing the individual baseline performance levels, integrating an individual progression of task complexity, and training load based on these assessments. Moreover, these techniques allow to give individual feedback and integrate motivational aspects (e.g., reaching the next performance level).

Other studies found improvements of exergames on fine motor skills (Ordnung et al. 2017) or ST walking (Pichierri et al. 2011). Finally, improvements on cognitive-motor task performance like the Timed Up and Go cognitive test (TUG; Schoene et al. 2015) and for DT walking (Pichierri et al. 2011) were described. Furthermore, brain imaging studies have demonstrated that DCMT more specifically changes the anatomy of neural substrate as a consequence of chronic use in specific information processing tasks, like changes in grey matter volume, etc. induced by motor-cognitive exergaming (Monteiro-Junior et al. 2016).

Patients In addition to these results of older adults, a systematic review and meta-analysis including studies with different populations (e.g., multiple sclerosis, post-stroke hemiparesis, Parkinson's disease, dementia, dyslexia, Down syndrome) showed that active exergaming including cognitive-motor interactions can improve EF and visuospatial perception (Mura et al. 2017). The authors concluded that exergames are an effective tool for rehabilitation of cognitive and motor functions in adult populations suffering from various neurological disabilities and developmental neurological disorders (Mura et al. 2017). These results were confirmed by a short review of Costa et al. (2019). The authors also added findings of benefits for balance control (Costa et al. 2019). Moreover, findings from Anderson-Hanley et al. (2017) indicate that exergames might be useful for the management of behavioral disturbance and for increasing cognitive control in children on the autism spectrum.

Summary of DCMT

This area of exercise is one of the intervention forms that have been examined extensively for all target groups presented here. Digital or virtual training interventions have great potential to improve cognitive-motor performance and accompanying processing speed. Within the different populations, DCMT was suitable to improve motor skill learning, including ball handling, fine motor performance, hand-eye coordination, driving, balance, and walking. Also, cognitive performance including math scores, EFs, divided attention, as well as multiple object tracking was enhanced, partially with accompanying changes in neurophysiological correlates (reported for older adults). The most beneficial duration is not clear; however, it seems that the duration should be at least 12 sessions with 30–45 min. In addition, these interventions have great potential for adaptivity, feedback, and progression. Nevertheless, it needs to be mentioned that most studies reported within-group improvements in exergamers and favorable interaction effects compared to passive controls. Studies that compared effects to other active control groups did not necessarily find superior effects of exergaming over physically active control groups and, if so, solely for executive functions.

5 Summary of Evidence and Future Directions – Potentials of Cognitive-Motor Multitasking Training for Different Target Groups

In summary, the preceding chapter has demonstrated that cognitive-motor training interventions have the potential to improve cognitive, motor, and cognitive-motor performance. For all different training forms, studies have demonstrated positive effects. Most of the studies only used performance measures on a behavioral level; however, first studies reported positive changes of related neurophysiological correlates.

Despite the overall positive effects, there are some differences in the effectiveness of the different trainings with respect to the nature of the training but also with respect to the training goals. SCMT has the potential to improve motor, cognitive, and cognitive-motor performance. Different target groups already benefited if the training duration was four weeks with a frequency of three sessions. The aspect of specificity allows to integrate individualization of training complexity and load as well as progression. However, it remains unclear whether the improved skills can be transferred or adapted to new task situations.

For GCMT, evidence showed that these interventions improve motor performance (balance and walking) under ST and DT conditions even in untrained task combinations. To gain these positive effects, at least a duration of eight weeks with a frequency of two times per week seems to be necessary. Yet, to counteract potential neurologically caused/age-related cognitive-motor impairments, the number of sessions needs to be increased. Moreover, as some studies failed to show benefits on cognitive-motor performance, one might conjecture that the composition of the actual training tasks is important. Training effectiveness crucially depends on a thorough selection of tasks and scheduling of training. If relevant training parameters are thoroughly controlled and adjusted, training gain will be increased, as it is also the case for SCMT.

TMMT successfully integrates the learning of relevant strategies to manage complex cognitive-motor situations. In order to do so, interventions should at least comprise of 12 sessions. Within these sessions, individualization and progression of training load and task complexity is required to increase cognitive-motor performance. In principle, the nature of this training regime could also contribute to skill learning. However, in our systematic overview on DT and multitasking training interventions, we were not able to identify a sufficient number of studies that actually reported instructions for task managing.

Finally, DCMT has great potential to improve cognitive-motor performance, particularly the underlying accompanying processing speed. Based on the actual study results, it seems that the duration should be at least 12 sessions with 30–45 min per session. As these interventions have great potential for adaptivity as well as individualization, feedback, and progression, which can be organized flexibly, they should gain more attention in the future.

Overall, the main body of the summarized literature investigated cognitive-motor training in older populations or participants with neurological diseases. Despite this bias, first results also showed positive effects for further target groups (children, adolescents, athletes). We therefore see the possibility and the potential to transfer knowledge about the training benefits from elderly or clinical populations to new areas of application. Especially, the target groups of (1) children and adolescents and (2) athletes in different sports might deserve more attention.

Future Directions for CMT with Children and Adolescents

If one intends to design multitasking interventions for children, necessarily, the different steps of cognitive-motor development need to be considered. For example attentional control, which is one basic component for cognitive-motor performance, develops throughout childhood and adolescence until young adulthood, in parallel with the development of the prefrontal cortex (Sowell et al. 2003; Steinberg 2005; Giedd et al. 2007) and the increasing differentiation of brain networks (Anokhin et al. 2000). There is evidence that children (approximately <9 years of age) less effectively attend to relevant stimuli than young adults (Davidson et al. 2006; Waszak et al. 2010). Therefore, children need competencies to adapt to the multitasking environments that surround them. Studies examining children (i.e., 7 years and older) found a U-shaped function between age and performance, showing larger switch costs (i.e., longer reaction times, more errors) than young adults (Courage et al. 2015). Moreover, the ability to maintain and manipulate two different tasks in working memory is only rudimentarily present in young children (Courage et al. 2015). Task-switching ability incorporating more complex rule structures rises with increasing age (Courage et al. 2015). On the other hand, the involvement of children in daily multitasking situations has risen over the last decades. A report from the Kaiser Family Foundation (Rideout et al. 2010) showed that children and adolescents spend about 8.5 hours per day using entertainment media (watching television or video, playing computer games, looking at websites, or messaging). These activities are accompanied with daily habits like eating, doing chores, talking on the phone, or completing homework, creating situations that might require precursors of multitasking abilities (Courage et al. 2015). These multitasking situations result in increased demands to divide attention between several attractors while playing or managing social interactions. In order to prepare for these challenges, it could be necessary to incorporate specific exercises to improve working memory and divided attention with increasing complexities into skill acquisition training (e.g., as shown by Koutsandreou et al. 2016; Lüder et al. 2018).

For adolescents, a review by Courage et al. (2015) reported that this target group, in contrast to younger children, can be described as the heaviest media multitaskers in school and other learning environments (Courage et al. 2015). The authors suggest that this target group is able to multitask (e.g., watch TV, scan e-readers, check e-mails, and communicate with friends through social media while studying) without any loss in performance (Courage et al. 2015). However, the authors also discuss the fact that these activities might be less complex and that task-switching costs might rise if the tasks become more mentally or physically demanding (Courage et al. 2015). Moreover, it is common sense that adolescents in comparison to adults have less abilities to concentrate. Therefore, it might be important to train abilities of task prioritization to reduce cognitive-motor decrements as a result of irrelevant task switching.

Future Directions for CMT with Athletes

There are several reasons why multitasking training interventions might also be beneficial for athletes or training for different kinds of sports in general. In open sports like different kinds of team sports (e.g., soccer, volleyball, basketball), there are many situations where the athletes have to manage different cognitive and motor processes at the same time. To be successful, all aspects of decision-making, distribution of attention, and different complex cognitive-motor processes need to be integrated seamlessly (Moreira et al. 2021).

Sport Science has a long tradition in dissociating functional components underlying plasticity, including *increased capacity*, *higher efficiency,* and *optimized task management.* However, these are often not explicitly considered yet, when designing cognitive-motor training programs. For athletes, cognitive-motor multitasking training is, so far, mostly integrated in coordination training, addressing specific and unspecific tasks of the sport (DiCesare et al. 2019). Yet, this kind of training deals with the sub-processes of multitasking more implicitly than explicitly. To date, there are only few studies on the benefits of a targeted, specific, and progressive multitasking training. However, as far as one can suspect from what is known so far, there is a great potential of SCMT, TMMT, and DCMT, particularly in a variety of team sports, to improve cognitive-motor performance and team interaction.

Integration of Theoretical Models of Cognitive-Motor Interactions into Future Training Regimes

The second part of this chapter referred to different models of performance limitations of the sub-processes in a cognitive-motor multitasking situation. Successful performance in a multitasking situation depends on an effective operation of several sub-processes. This, of course, includes the processing stream of the ST but also additional meta-processes, like goal setting, prioritization, scheduling, resource allocation, and evaluation, which are operating at different levels to conduct the interplay of all sub-processes (e.g., Burgess et al. 2000).

Moreover, resource allocation is driven by the requirements of the task, for example, it may be important whether processing involves object-based (e.g., the discrimination of stimulus attributes) or spatial attention (e.g., the localization of stimuli; Wahn and König 2017). Irrespective of the details of different models, ultimately, externally imposed task demands and internally generated task prioritization will define how individuals use sub-processes and allocate resources for the most appropriate outcome. Assuming interacting cognitive processes for motor execution, the related cognitive abilities need to be identified to design effective training regimes.

Unfortunately, there are still a lot of training studies that do not report any concepts on underlying performance factors and potential mechanisms defining the targets of their training regime. Moreover, the study results are often solely discussed on a behavioral level and do not reflect on underlying cognitive-motor interactions or resulting interference.

We therefore claim that in order to conduct an appropriate training intervention, the underlying storyboard with the specific requirements to improve relevant cognitive, motor, and cognitive-motor outcomes needs to be identified. This will lead to a general idea of the processes that are required to manage the tasks. Moreover, the conduction of an effective training should reflect the potential mechanisms that will be necessary to gain positive effects on different levels of performance.

Integration of Theoretical Models of Exercise Science into Future Training Regimes

Regarding the basic concepts and principles that could be integrated into a multitasking training (cf. Sects. 2 and 3 of this chapter), there is a lot of potential for interdisciplinary work. Within the area of cognitive training, common principles of exercise science might help to shape and improve training interventions, for example, by adding progression or task-managing instructions. On the other hand, training interventions, be it in sports games, professional activities, or our everyday life, can profit if the training relies more on underlying processes that have to be changed to gain more functionality.

However, as demonstrated in this chapter, many everyday tasks, professional activities, or competitive challenges require a sustained effort to increase, maintain, or even improve performance in cognitive-motor multitasking. The presented combined interventions, regardless of the actual training methods (specific, general, including strategy teaching, or virtual) seem to have a lot of potential for all training aims (motor learning or skill acquisition, performance optimization, and preservation of resources). There is some evidence that specific and task-managing training might be very effective, requiring relatively small amounts of practice to gain positive results on cognitive-motor performance. Therefore, these interventions should be recommended especially for the goal of motor learning, skill acquisition, and performance optimization. In order to maximize training efficiency for cognitive and motor benefits, the training might be most effective if the cognitive and motor components are trained simultaneously.

Based on the overall knowledge on multitasking training, the design of future training protocols for cognitive-motor training should follow five main steps:

(1) Description of the cognitive-motor tasks that are aimed to be improved

(2) Designing the storyboard of subtasks and dependent timelines of all relevant training components to gain training specificity
(3) Identifying underlying sub-processes that are required
(4) Decision on the type of training that is suitable
(5) Integrating the relevant training principles (A,P,S,I; Sect. 3.1)

Following these steps will allow you to systematically achieve the defined training goals (particularly steps 1–3). As we tried to point out, effectiveness is also modulated by many other factors like the temporal scheduling, the training dose, the momentary functional capacity of the system, etc. Therefore, steps 4 and 5 also need to be addressed properly in the planning but also while the training is actually conducted. The progress of a training regime should be monitored continuously, and all contents should be adopted with respect to the individual progress of the trainees or target group. Thoroughly considering these steps will not only contribute to securing the intended training success, it will also help to make methodological decisions explicit and thereby help to better compare and integrate the results of future scientific studies.

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The Multitasking Motorist

David L. Strayer, Spencer C. Castro, and Amy S. McDonnell

In this chapter, we consider multitasking in the context of driving to involve the performance of two or more *functionally independent tasks* with separate goals, stimuli, and responses.[1] We contrast this definition with performing *functionally interdependent tasks* that serve common or overlapping goals. The concurrent use of a smartphone while operating a motor vehicle epitomizes everyday multitasking. At any given daylight moment, 9.7% of the driving public in the United States can be seen holding their smartphone to talk or text while operating a motor vehicle (DOT 2019). Drivers also use Bluetooth-enabled in-vehicle infotainment systems to perform a variety of secondary tasks (Strayer et al. 2019). This ubiquitous multitasking activity distracts drivers and leads to increases in injuries and fatalities on our roadways (WHO 2011). Note that the driving task and the smartphone task are functionally independent. They have separate goals (transportation vs. communication) with distinct stimuli (the driving environment vs. the content of the conversation) and responses (e.g., steering and braking vs. talking and listening). By contrast, interdependent tasks support the same overall goal (e.g., maintaining vehicle control through speed and space management by looking at the speedometer and adjusting the accelerator to control vehicle speed and making steering inputs to stay in the lane of travel).

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[1] We use the terms multitask and dual task interchangeably in this chapter. A dual-tasking situation is one in which participants perform two functionally independent tasks. Multitasking is a more generalized term in which participants concurrently perform two *or more* independent tasks.

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The limits of human attention govern both functionally independent tasks and interdependent tasks. They also both can lead to impairments in driving performance when they are performed concurrently with the task of driving. Regan et al. (2011, p. 1776) defined the distraction created by performing functionally independent tasks (i.e., "*driver diverted attention*") as "the diversion of attention away from activities critical for safe driving toward a competing activity, which may result in insufficient or no attention to activities critical for safe driving." In the smartphone example described above, talking and texting are unrelated activities that divert attention away from the primary task of driving. Regan et al. (2011, p. 1975) defined the impairment from performing functionally interdependent tasks (i.e., "*driver misprioritized attention*") as "insufficient or no attention to activities critical for safe driving brought about by the driver focusing attention on one aspect of driving to the exclusion of another, *which is more critical for safe driving*." In the second example described above, looking at the speedometer (a less critical activity) may divert attention from the more critical task of lane maintenance. The essential difference between these two categories stems from whether attention is directed away from safety-critical aspects of driving to a secondary task that is unrelated to driving (i.e., an independent task) or to a secondary task that is related to driving but is less critical to roadway safety (i.e., an interdependent task).

Herein we consider the safety-critical aspects of driving to be the *primary task.* When performed concurrently, activities unrelated to or less safety-critical than driving become *secondary tasks*. However, this distinction is somewhat arbitrary, as one could easily imagine the perverse situation in which the driver considers the conversation to be the primary task and driving to be secondary. Some oblivious drivers may even think that the task of driving gets in the way of conversing when safety considerations, state laws (GHSA 2020), and common sense dictate that driving should be the primary task.

When motorists perform a secondary task, the attention allocated to the more safety-critical aspects of the driving task decreases. Given the limited pool of attentional resources (Kahneman 1973), there is a reciprocal relationship between the attention allocated to the primary and secondary tasks—as the cognitive demands of the secondary task increase, the allocation of attention to the core driving task decreases (Navon and Gopher 1979). Importantly, secondary tasks vary in both mental and temporal demand. Some secondary tasks are relatively easy and are performed quickly, whereas other secondary tasks are much more cognitively demanding and take considerably longer to perform. Consequently, there is a wide variation in the effects of multitasking on driving performance.

1 SPIDER

As motorists navigate their vehicle from one location to the next, they must maintain good speed and space management, identify and react to actual threats, identify potential hazards, and follow information governing traffic flow (e.g., obey traffic lights). Many of the essential activities that a driver performs depend on attention; to be safe, a driver must "pay attention" to the driving environment. Strayer and Fisher (2016) developed a model that summarizes the literature and characterizes many of the impairments to driving that occur when a driver multitasks. The model called SPIDER is an acronym that stands for **S**canning, **P**redicting, **I**dentifying, **D**eciding, and **E**xecuting **R**esponses. As illustrated in Fig. 1, the driving literature establishes that each of these cognitive operations is impaired when drivers multitask, and consequently, multitasking results in an impairment to the motorist's awareness of the driving environment (i.e., their situation awareness).

Scanning Drivers must visually scan the driving environment to navigate safely, stay in their lane of travel, and avoid obstacles. This term includes looking at the forward roadway, scanning the periphery, glancing at side and rear-view mirrors, and monitoring the instrument cluster. When a driver multitasks, they tend to narrow their gaze to a restricted region of the forward roadway, often neglecting the other sources of visual information that are critical to safe driving (e.g., Briggs et al. 2017; Engström et al. 2005; Harbluk et al. 2007; He et al. 2011; Horrey et al. 2006; Recarte and Nunes 2000; Reimer 2009; Reimer et al. 2012; Strayer et al. 2017; Tsai et al. 2007; Victor et al. 2005). Others have referred to this facet of driver behavior as *gaze concentration* or *visual tunneling* (e.g., Reimer 2009; Wang et al. 2014).

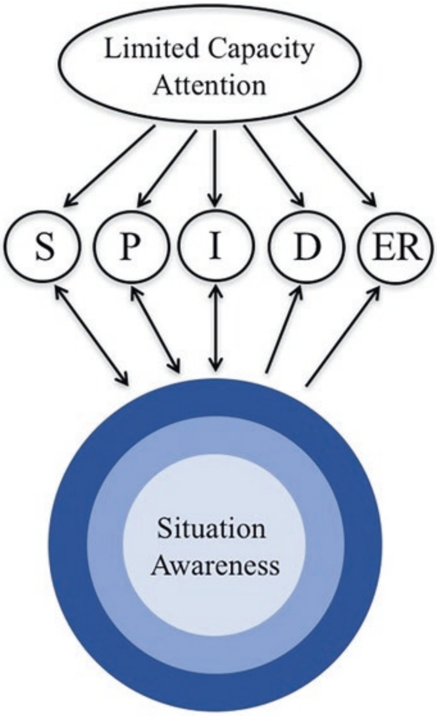

Fig. 1 The SPIDER model is an acronym for **S**canning, **P**redicting, **I**dentifying, **D**eciding, and **E**xecuting a **R**esponse. Multitasking diverts attention from driving, causing the motorist's situation awareness to be reduced. This is illustrated by progressively smaller and lighter-shaded concentric circles. The bidirectional arrows show that situation awareness is informed and updated by the SPIDER-related processes (i.e., scanning, predicting, and identifying) and facilitates expectancy-based processing of the driving scene. The loss of situation awareness impairs driving performance and increases the relative risk of a crash

Predicting Hazard prediction is an essential component of safe driving. To avoid being caught in the moment, motorists must use their driving experience to anticipate where potential threats might arise. For example, when passing a bus stopped adjacent to a crosswalk, an experienced motorist often looks at locations where pedestrians could cross in front of the bus. Notably, anticipatory glances associated with hazard prediction move to locations where a *potential* hazard may appear (i.e., these are glances to a location). Multitasking drivers show deficits in this anticipatory behavior, often exhibiting hazard prediction behavior more similar to that of a novice driver (Taylor et al. 2015). In an on-road study, Biondi et al. (2015) found that multitasking impaired the likelihood of making a glance to check for pedestrians in a crosswalk.

Identifying A driver must attend to the visual input to determine what they are looking at. Attention is necessary to transfer this information into working/short-term memory (e.g., Atkinson and Shiffrin 1968). Multitasking drivers often fail to see objects in their line of sight, leading to a phenomenon referred to as *inattentional blindness* (Mack and Rock 1998; Simons and Chabris 1999; Strayer et al. 2003; Strayer and Johnston 2001). For example, Strayer et al. (2004) found that drivers failed to identify up to 50% of the information they looked at (as verified using eye-tracking measures) when they were conversing on a hands-free cell phone.

Deciding Drivers are often faced with deciding between two or more options. For example, in the lane change task (ISO DIS 26022 2010), drivers must decide when to shift from the center lane of travel to either the left lane or the right lane. When drivers multitask, they often fail to fully evaluate the alternative sources of information. Indeed, Cooper et al. (2009) found that multitasking drivers were more likely to make unsafe lane changes. Cooper and Zheng (2002) also found that multitasking drivers were more likely to misjudge the gap size and the speed of oncoming vehicles, and this deficit was most apparent on wet roadways.

Executing Response When faced with an unexpected event, motorists are often required to take evasive action (e.g., make steering or braking response). When drivers multitask, these actions often become delayed (Atchley et al. 2017; Caird et al. 2008; Horrey and Wickens 2006). Moreover, multitasking tends to positively skew the brake RT distributions so that late responses become particularly slow (Ratcliff and Strayer 2014). These sluggish brake reactions increase the likelihood and severity of crashes (Brown et al. 2001).

Situation Awareness A motorist's mental model of the driving environment—their situation awareness—is governed by the SPIDER-related processes (see Fig. 1). When drivers multitask, their situation awareness can become compromised (e.g., Durso et al. 2007; Endsley 1995, 2015; Horrey et al. 2006; Kass et al. 2007). The degradation of situation awareness depends upon both the mental and temporal demands of the secondary task being performed. Greater impact occurs with longer and more demanding secondary tasks. In Fig. 1, the bidirectional arrows from scanning, predicting, and identifying to situation awareness correspond to Endsley's (1995) three levels of situation awareness. Level 1 situation awareness relates to the perception of elements in the current situation. Level 2 situation awareness relates to comprehension of the current situation. Level 3 situation awareness relates to the prediction of the situation's future status. The bidirectional links indicate a recurrent process where scanning, predicting, and identifying update the driver's mental model, which can serve as a basis for adjustments in the amount of attention allocated to each of these processes. The fidelity of a motorist's awareness of the driving situation governs their decisions and the speed of their responses.

Endsley (1995) discusses how even small lapses in situation awareness result in poor performance. As illustrated in Fig. 1, greater demands on limited-capacity attention (caused by multitasking) result in impairments to the SPIDER-related processes and decrements in a motorist's situation awareness. Greater secondary-task demand results in lower levels of situation awareness. Figure 1 represents this effect with progressively smaller and lighter concentric circles. In their simulations, Fisher and Strayer (2014) found that a 5% decrease in the likelihood of any of the SPIDER-related processes being completed successfully would double the relative risk of a crash.

2 Measurement of Cognitive Distraction

Strayer et al. (2015) measured the effects of a variety of secondary tasks on a driver's workload. Simple tasks like listening to a radio or an audiobook were associated with low cognitive demand and did not adversely impair driving performance. By contrast, conversation tasks (e.g., talking to an interlocutor sitting next to the driver or conversing on a hand-held or hands-free cell phone) led to significantly higher levels of workload and greater impairments to driving than listening to the radio or audiobook.

Conversation is a dynamic process that involves both speech comprehension and speech production. Strayer et al. (2017) measured the cognitive workload of the conversational dyad (i.e., driver and non-driver) as they engaged in a natural conversation. The authors evaluated both an in-person (i.e., a passenger conversation) and a remote hands-free cell phone conversation. To obtain dynamic measures of workload, these authors used a specially configured version of the detection response task (DRT; International Standards Organization (ISO DIS 17488 2015)). Every 3–5 seconds, "yoked" DRT devices (one fitted to the driver and one fitted to the non-driver) flashed a light in the peripheral field of view of the left eye of each member of the conversational dyad. Both the driver and non-driver responded separately to the onset of the light by pressing a microswitch attached to their finger. Additionally, each DRT was equipped with a microphone to determine if the driver or non-driver was talking or listening at any point in time.

The DRT is very sensitive to dynamic fluctuations in mental workload; RT increases as the cognitive demands of a task increase.[2] In Fig. 2, the mental load of the driver is represented by the solid line. The "single task" refers to the DRT measurements obtained from the driver when they are performing the primary task of operating the vehicle (i.e., the driver was not multitasking). Note that when the driver begins to multitask by concurrently conversing with the non-driver, DRT reaction time systematically increases. Importantly, the increase in reaction time is the same for both the passenger conversation (i.e., when both the driver and non-driver are seated in the same vehicle) and cell phone conversation (i.e., when the conversational dyad is not in the same location).[3] Moreover, DRT reaction time is longer when the driver is talking (i.e., DT) than when they are listening (i.e., DL). A reciprocal pattern can be observed in Fig. 2 with the non-driver (depicted by the dotted line). Here again, DRT reaction time is equivalent for passenger and cell phone conversations, and it is longer when the driver is listening (and the non-driver is talking) than when the driver is talking (and the non-driver is listening).

The dynamic fluctuation in workload observed for both the driver and non-driver indicates that speech production is, on the whole, more demanding than speech comprehension. When the driver attempts to converse while operating their vehicle (i.e., when they multitask), their workload is higher than that of the non-driver. That is, the conversational dyad produces a pattern of resource reciprocity and the data indicate that driving competes for the same limited resources as the conversation. Also noteworthy is the ebb and flow of the multitasking costs with the dynamics of an unfolding conversation.

Subsequent research measuring the effects of a secondary task on a driver's workload has found that using a smartphone to interact with an intelligent personal

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[2] The DRT involves presenting a simple stimulus every 3–5 seconds and requiring drivers to make a simple button press (i.e., the DRT is a simple RT task). The DRT is an ISO protocol (ISO DIS 17488 2015) for measuring a driver's workload, but it clearly adds another unrelated task to the mix that has the potential to alter the driver's performance, thereby creating an example of the Heisenberg principle where measuring workload may alter the driver's behavior. In fact, Castro et al. (2019) found that the introduction of the DRT with an easily perceived light slightly degraded pursuit tracking performance, but not as much as a light that was more difficult to perceive or when the DRT task was changed from a simple RT task to a choice RT task. By contrast, Strayer et al. (2015) found that subjective workload was not altered with the introduction of the DRT and, in another context, Palada et al. (2019) found that the DRT did not interfere with the primary task of classifying maritime ships as friend of foe. On the whole, there is little evidence that the DRT significantly alters performance of the primary driving task. Nevertheless, care must be taken with the use of the DRT to ensure that the protocol does not introduce a confound in the experimental design.

[3] Despite the fact that the cognitive workload experienced by the driver is the same for cell phone and passenger conversations, the risk of a motor vehicle crash is considerably higher for the former (i.e., the odds ratio of a crash when conversing on a cell phone is 4.2; McEvoy et al. 2005; Redelmeier and Tibshirani 1997) than for the latter (i.e., the odds ratio of a crash is 0.7 when an adult passenger is in the vehicle; Rueda-Domingo et al. 2004; Vollrath et al. 2002). This discrepancy can be explained, in part, by the fact that adult passengers often support the driver by pointing out hazards and helping the driver to navigate (Drews et al. 2008).

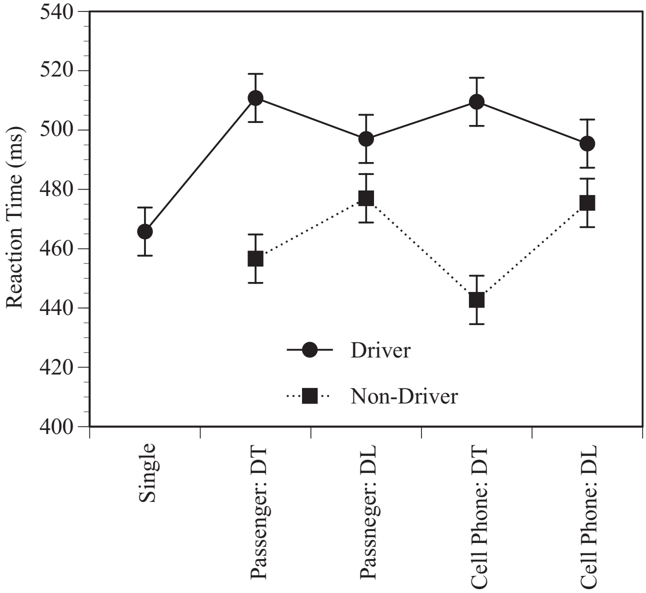

Fig. 2 Reaction time for the driver and non-driver when they respond to the DRT. Error bars reflect the standard error of the mean. The single-task condition reflects performance when the driver is driving and not conversing. The "passenger" conditions reflect a conversation when both members of the dyad were seated in the same vehicle. The "cell phone" conditions refer to a remote hands-free cell phone conversation. DT refers to situations when the driver is talking and the non-driver is listening. DL refers to situations where the driver is listening and the non-driver is talking

assistant (e.g., Apple's *Siri*, Google's *Google Now,* and Microsoft's *Cortana*) resulted in even higher levels of cognitive workload than conversation tasks (Strayer et al. 2017). In fact, using an intelligent personal assistant to send simple text messages resulted in the same cognitive load as performing an auditory version of the mind-numbing Operation Span (OSPAN) Task[4] while driving (Watson and Strayer 2010), well above any reasonable red line of workload (Grier et al. 2008). Taken together, there is considerable variability in the mental workload associated with different multitasking operations.

When motorists multitask, their awareness of the driving environment degrades over time (e.g., for a review, see Strayer and Fisher 2016), and they are less able to react to unexpected events. Figure 3 depicts a model of the loss and recovery of attention to driving across a multitasking episode.[5] In the figure, the diameter of the

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[4] The OSPAN task is a complex memory span task developed by Turner and Engle (1989) that requires participants to hold items in memory while concurrently solving simple math problems and then to recall the memorized items in the order that they were presented.

[5] Figure 3 presents a conceptual depiction of the bandwidth of the information processing system of the driver based upon the mathematical framework of signal processing developed by Claude

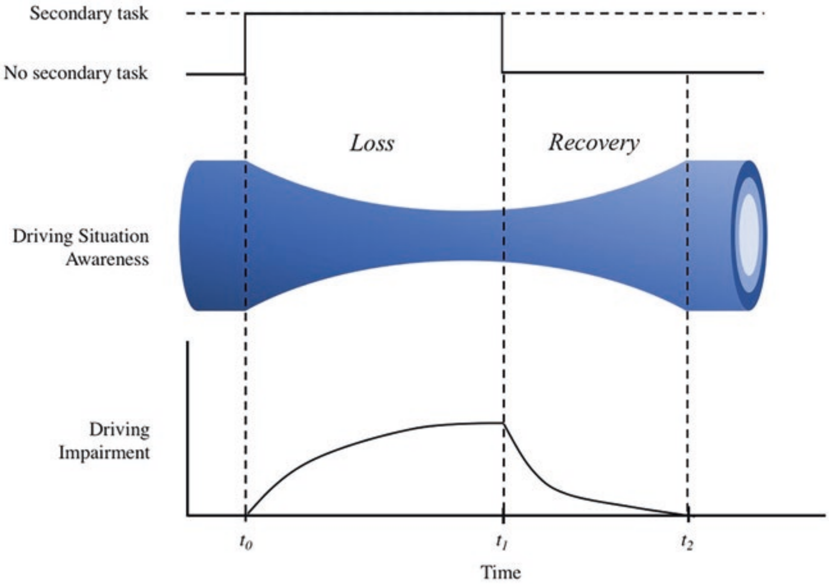

Fig. 3 Dynamic fluctuations in attention plotted as a function of a multitasking episode. The diameter of the cylinder reflects the amount of attention allocated to the driving task. The larger the diameter, the greater the amount of attention allocated to the driving task

cylinder represents the moment-to-moment level of capacity allocated to driving, with a larger diameter indicating more attention to the driving task. In the period preceding t_0, the motorist is shown performing the single-task of driving and attention allocated to the task is high. At t_0, the driver begins to engage in an attention-demanding secondary task (i.e., they begin to multitask), and attention is diverted from the processes requisite for safe driving. Driving impairments from multitasking grow between t_0 and t_1. At $t_{1,}$ the motorist stops performing the secondary task, and attention is redirected to the primary task of driving. Impairments to driving dissipate between t_1 and t_2. At t_2, attention has been fully returned to the driving task (i.e., performance has returned to single-task levels). The model shown in Fig. 3 has symmetrical loss and recovery functions; however, this is not a requirement of the model.

Shannon (1948). The greater the bandwidth or channel capacity of a system (depicted in Fig. 3 by the diameter of the cylinder), the more information that can be processed per unit time. Information theory (e.g., Hick 1952; Hyman 1953) describes the relationship between bandwidth, processing speed, and also the loss of information due to capacity limits (e.g., bottlenecks in information processing due to multitasking that can lead to impaired driving). In Fig. 3, the bandwidth of processing of the driving task is reduced between t_0 and t_2 because attention has been diverted to a secondary task.

3 Persistence of Distraction

The recovery from multitasking can be empirically determined by plotting the residual costs following a multitasking episode. Strayer et al. (2016) used the DRT procedure described above (i.e., probing randomly every 3–5 seconds) to measure the residual costs after a driver issued a voice command to tune the radio or to place a phone call. These voice-based features are common in new automobiles and often involve pushing a button on the steering wheel and then speaking a command (e.g., tune the radio to 90.1 FM). Figure 4 presents the residual costs plotted in 3-second intervals across the post-multitasking window. For comparison, the red "O" represents DRT performance when participants were driving and concurrently performing the OSPAN task and the red "S" indicates DRT performance in the single-task driving condition. The red dotted line marks the level at which DRT performance was significantly greater than the single-task baseline. The best-fitting power function, plotted in blue, shows large costs immediately after the multitasking episode had finished. These costs dissipate as a negatively accelerated function of time over the 30-second post-multitasking window. In fact, 3 seconds after multitasking stopped, the residual costs were the same as when drivers had been concurrently performing the OSPAN task. The residual costs were significantly different from single-task baseline 27 seconds after multitasking had terminated. It is noteworthy that the residual costs observed in this study lasted longer than the actual multitasking episode.

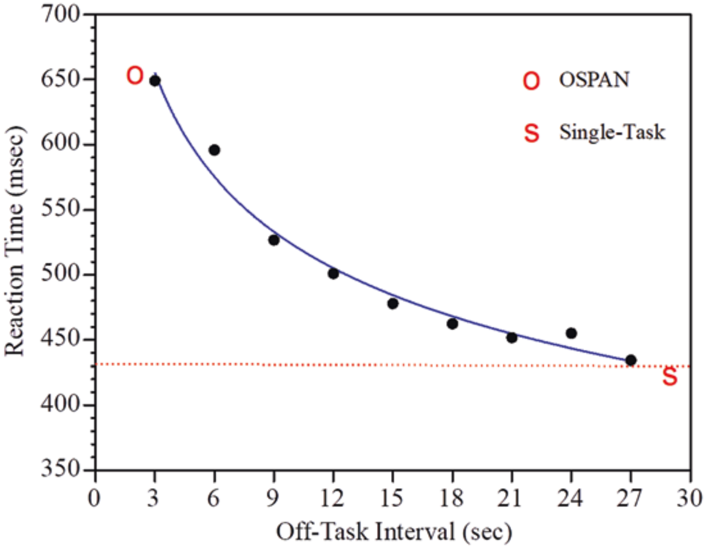

Fig. 4 Residual costs as measured by the DRT following a multitasking episode. For comparison, O indicates performance when concurrently performing the OSPAN task and S reflects performance on the single-task of driving

In reference to Fig. 3, the interval between t_1 and t_2 was 27 seconds for drivers using these common in-vehicle voice commands. These multitasking costs were hidden because there was no overt secondary task being performed by the driver when they were obtained. The DRT methodology provides a valuable tool to unveil these hidden multitasking costs by probing throughout the drive. However, Jenness et al. (2015) reported a similar recovery pattern with measures of driving performance (e.g., steering inputs and driving speed) and Turrill et al. (Submitted) observed residual costs in eye-tracking measures (e.g., pupil diameter, which has been found to vary with mental workload; Ahern and Beatty 1979; Beaty and Lucero-Wagoner 2000; Kahneman and Beatty 1966).

These behavioral and physiological measures establish that the residual costs are not an artifact produced by the DRT methodology. Turrill et al. (Submitted) also found that the duration of the residual costs following a multitasking episode (i.e., the interval between t_1 and t_2 in Fig. 3) was modulated by driving difficulty (manipulated by traffic density in a driving simulator) and secondary-task load (manipulated by counting backward by 1s or 3s). By contrast, Turrill et al. (Submitted) found that the impairments were apparent shortly after initiating the multitasking episode (i.e., the interval between t_0 and t_1 in Fig. 3). This demonstrates that the loss and recovery functions depicted in Fig. 3 are, in fact, asymmetrical. The impairments are manifested soon after multitasking begins whereas the recovery from multitasking takes about half a minute (or more) to dissipate.

It is worth considering the mental operations associated with starting and stopping a multitasking episode. When starting to multitask, motorists must load the secondary-task goals and procedures into working memory and then hold and manipulate that information (Baddeley and Logie 1999; Engle 2002). They must juggle the two tasks, switching between them to support the task demands (e.g., Salvucci 2006; Salvucci and Taagen 2008). Turrill et al. (Submitted) found that it took just a few seconds for participants to get a secondary counting task going. For simple dual-task combinations (e.g., counting backward by 1s while performing a simple pursuit tracking task), the dual-task costs were apparent within 3 seconds (i.e., within the resolution of the DRT measurement procedure). With more complex dual-task combinations (e.g., counting backward by 3s while driving a simulated vehicle in high-density traffic), dual-task costs were fully apparent by 6 seconds. A reasonable interpretation of these data is that the goals and procedures supporting counting backward by 3s take longer to load and manipulate in working memory than counting backward by 1s. This interpretation is supported by subjective reports from participants that it took longer and was harder to get the more demanding counting task underway.

As of 2020, 48 states prohibit texting while driving (IIHS 2020). Although the laws vary state by state, the majority prohibit texting while driving, even if stopped at a red light. Motorists may wonder why smartphone use is prohibited when the vehicle is stopped. What could possibly go wrong if the vehicle is stopped? The residual costs shown in Fig. 4 provide a rationale for why texting at red lights is unsafe. When the light turns green, drivers may proceed into the intersection with impaired situation awareness (Strayer and Fisher 2016) and the residual costs from multitasking are likely to persist for the duration of the transit through the intersection. The impaired situation awareness means that multitasking motorists are often unaware of pedestrians, bicycles, and other obstacles on the roadway and in the crosswalk. Rates of injuries and fatalities to pedestrians and bicyclists have seen a sharp uptick in recent years, due at least in part to drivers multitasking at intersections. In fact, since 2009, pedestrian fatalities have risen by 53% (IIHS 2018). A portion of the increase in fatalities is also likely due to multitasking pedestrians who also use their smartphones when crossing the road. They also suffer from a loss of situation awareness and may step into the crosswalk without looking to see if it is safe to do so. Indeed, in 2017, the city of Honolulu enacted a prohibition of pedestrians using their smartphones while crossing the street (Honolulu 2017).

4 Threaded Cognition

Salvucci and Taagen (2008) developed a *threaded cognition* theory of multitasking to account for the costs incurred when people concurrently perform unrelated tasks such as driving and counting backward (or conversing on a smartphone). Based on the ACT-R (Adaptive Control of Thought-Rational) architecture, threaded cognition assumes that a serial cognitive processor coordinates the multiple task "threads" associated with currently active tasks. The theory instantiates an "exclusive-use" rule whereby requests for processing for other threads must wait until the completion of the current process. A procedural bottleneck arises when competition for the exclusive-use cognitive processor occurs. The exclusive-use rule causes behavior to be restricted to a single thread, a feature of cognition likely to minimize crosstalk between multiple task threads (e.g., Bergen et al. 2013). Threaded cognition posits that task threads acquire processing resources in a "greedy" fashion and release them "politely." A greedy thread requests processing resources as soon as possible when they are needed, although the thread may have to wait its turn because of the exclusive-use rule. A polite thread releases resources for other threads as soon as its processing is no longer required. Finally, the task threads are prioritized so that the least recently processed thread receives priority.

Because the cognitive processer operates on an exclusive-use rule, combining an attention-demanding secondary task with driving results in contention for cognitive processes and suboptimal driving performance (as well as suboptimal performance on the attention-demanding secondary task). Effectively, the current task thread locks out other threads from the central processor until processing on the current thread has been completed. An example of this bidirectional interference is apparent in Fig. 2. Relative to the single-task driving condition (i.e., that of the driver) and the single-task conversation (i.e., that of the non-driver), performance on both tasks was degraded when the driver attempted to combine them. This pattern in Fig. 2 is consistent with the prediction that the conversation thread locks out the driving thread and the driving thread locks out the conversation thread.[6]

The robust residual costs following a multitasking episode depicted in Fig. 3 are much larger than would be expected from the psychological refractory period (PRP; Pashler 1994, 2000) or task switching (e.g., Rogers and Monsel 1995) literature. It is noteworthy that these residual costs were observed with DRT measurements (both RT and hit rate to the DRT stimulus) when a real-world driving task was paired with voice-based interactions in the vehicle. They were also observed with a simple pursuit-tracking task and with a high-fidelity driving simulator when participants drove and performed a backward counting task. Additionally, they were observed with measures of driving performance and with physiological measures.

The residual costs presented in Fig. 3 are inconsistent with the concept of a "polite" thread that releases resources as soon its processing is no longer required (Salvucci and Taagen 2008, p 110). It would appear that the threads are anything but polite, with residual costs persisting for half a minute or more. It is possible that the DRT measures reflect the motorists "catching up" on driving threads that have been neglected during multitasking. For example, a driver's situation awareness degrades over the multitasking episode (Strayer and Fisher 2016). Once the secondary-task thread has terminated, processing resources may be returned to the driving task to refresh the mental model of the driving environment.

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[6] The pattern presented in Fig. 2 was obtained using the DRT protocol. This protocol involves presenting a simple stimulus and requiring the driver to make a simple button press (a simple RT task) and, as discussed above, the procedure causes little or no interference with other ongoing tasks. How would threaded cognition account for the sensitivity of the DRT to primary and secondary-task demand? One possibility would be that a DRT thread gets added to the goal buffer. For example,

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IF the goal buffer contains a triple task (e.g., the driving task, a secondary-task, and the DRT task)
THEN add the goal to perform the driving task
and add the goal to perform the secondary task
and add the goal to perform the DRT task.
…
If the goal buffer contains the DRT task
and the DRT stimulus has been presented
Then issue the DRT motor response.
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The exclusive-use rule would cause the DRT thread to wait its turn in the goal buffer until other threads had been completed. Consequently, the more demanding the driving task and/or the more demanding the secondary task, the longer the latency of the DRT response. Note that because of the simplicity of the DRT task, the DRT thread should take few processing resources and would therefore produce little interference with the primary and secondary tasks. However, the rule that the least recently processed thread receives priority would seem in need of modification to a first-in, first-out rule. Otherwise, the intermittent DRT task would take priority over the continuous driving and secondary tasks. This follows because, when paired with continuous tasks (e.g., driving and conversing), the DRT would often be the least recently processed thread and would take priority over the other tasks. Under such a scenario, the DRT would be insensitive to primary- and secondary-task difficulty. Because the DRT is very sensitive to primary- and secondary-task difficulty, the DRT thread must wait its turn in the goal buffer.

One potential source of evidence for enhanced driving-related processing in the post-multitasking interval could come from eye-tracking measures. It is well established that drivers concentrate their gaze toward the center of the roadway when they perform a cognitively demanding secondary task (e.g., Harbluk et al. 2007; Victor et al. 2005). Informative glances to side mirrors and to the periphery decrease while multitasking. Turrill et al. (Submitted) examined visual scanning patterns in the pre-multitasking, multitasking, and post-multitasking intervals (i.e., prior to t_0, from t_0 to t_1, and from t_1 to t_2 in Fig. 3, respectively) to see if there was an increase in peripheral scanning once the secondary task had terminated. However, instead of enhanced peripheral visual scanning, the pattern revealed was that of a gradual return to single-task levels similar to the pattern in Fig. 3. No evidence appeared in the eye-tracking measures that drivers attempted to "catch up" with enhanced visual scanning in the periphery once the secondary task had stopped. Moreover, the residual costs were also observed in a simple pursuit-tracking task where there was little, if any, situation awareness to regain after multitasking. Although the absence of evidence is not evidence of absence, we found no direct evidence to support the "catch-up hypothesis."[7]

If motorists are not catching up on driving threads neglected while multitasking, what is the source of the residual costs? One possibility is that there is a passive decay of the information held in working memory associated with the completed secondary task. Whereas Turrill et al. (Submitted) found that loading information into working memory occurred relatively quickly, the purging of this information appears to be more gradual (i.e., similar to that of the Brown-Peterson short-term memory forgetting functions, Brown 1958; Peterson and Peterson 1959). This now irrelevant information continues to occupy valuable space in working memory and cause interference and crosstalk with the information necessary for driving. Evidence supporting the passive decay hypothesis comes from eye-tracking measures that show a gradual decrease in pupil dilation over the post-multitasking interval (Turrill et al. Submitted). The eye-tracking measures suggest a gradual decrease in cognitive interference as the secondary-task information decays.

5 Crosstalk Hypothesis

William James was one of the first to comment on the fact that the more similar two tasks are, the more they are likely to interfere with each other when they are performed concurrently (James 1890). The crosstalk hypothesis suggests that dual-task

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[7] The residual costs were observed in the DRT and in measures of pupil diameter. Importantly, Jenness et al. (2015) reported residual costs in steering inputs and driving speed, measures of performance obtained with the primary task of driving. Perhaps the strongest evidence that more than "catching up" is happening in the post-multitasking interval comes from the fact that similar residual costs are observed in a simple pursuit-tracking task where there is little if any situation awareness to recover.

interference occurs when two tasks use similar or overlapping information that come into conflict (e.g., Bergen et al. 2013; Navon and Miller 1987; Pashler 1994). Crosstalk, sometimes described in the literature as "code conflict," can occur in perception, in working memory, and in motor output. Similar (but functionally independent) tasks using similar information can be confusing for the information processing system to sort out. For example, in threaded cognition (Salvucci and Taagen 2008), the different task threads could act upon the wrong information held in working memory. When multitasking stops, the (now) irrelevant secondary-task information slowly fades from working memory and crosstalk diminishes.

Bergen et al. (2013) differentiated between *domain-general interference*, brought about by a competition for limited attentional resources (e.g., Kahneman 1973) and *domain-specific interference*, brought about by concurrent demands on the "mental machinery." Crosstalk is an example of domain-specific interference. Bergen et al. (2007) provide an example of crosstalk where the spatial and linguistic aspects of visual imagery compete because they place demands on the same neural hardware. Crosstalk occurs while multitasking when the specific mental representations and procedures conflict—the greater the overlap, the greater the potential for crosstalk.

From the perspective of crosstalk, driving and conversing on a hands-free cell phone would seem to be an example of two tasks that could be combined with little dual-task interference. Driving is thought to be a task that uses visual information, spatial codes, and manual responses. By contrast, conversation is thought to be a task that uses auditory information, verbal codes, and vocal responses. Multiple resources accounts would suggest little competition between the two tasks because they use different modalities of input, different mental codes, and different response types (Wickens 1980, 1984, 2008). However, there is abundant evidence that these two tasks compete on a variety of levels (cf., Strayer and Fisher 2016).

Bergen et al. (2013) point out that comprehension and production of language often involve mental simulation. In their study, they had participants characterize the veracity of sentences with motor content (e.g., "To open a jar you turn the lid counterclockwise"), visual content (e.g., "The letters on a stop sign are white"), and abstract sentences with no clear motor or visual context (e.g., "The capital of North Dakota is Bismarck"). The different sentences, thought to elicit different patterns of mental simulation, resulted in different patterns of dual-task interference when they were paired with driving. One the one hand, brake reaction time was found to be equally impaired by all sentence types, providing support for domain-general interference. On the other hand, processing sentences with visual scenes produced more interference on measures of following distance than abstract sentences, providing support for domain-specific interference. The lesson from this research is that language with different content recruits different neural hardware and produces different patterns of dual-task interference.

It may not come as a surprise that the destination-entry features supporting navigation found in many new vehicles produced the greatest potential for distraction (Strayer et al. 2019). There are high levels of crosstalk between programming a GPS navigation system and operating a motor vehicle because of the overlapping visual, cognitive, and manual demands of the two concurrent tasks. In fact, the National

Highway Traffic Safety Association's visual-manual guidelines (NHTSA 2013, p. 116) recommend against in-vehicle electronic systems that allow drivers to interact with a navigation system supporting destination entry when the vehicle is moving.

6 Hierarchical Control and Driving

Surprisingly, some aspects of driving significantly improve when drivers multitask. For example, a number of researchers have found that drivers maintain better lane position when they engage in a demanding cognitive secondary task (Atchley and Chan 2011; Becic et al. 2010; Beede and Kass 2006; Brookhuis et al. 1991; Engström et al. 2005, He and McCarley 2011; Horrey and Simons 2007; Horrey and Wickens 2006; Jamson and Merat 2005; Knappe et al. 2007; Liang and Lee 2010; Östlund et al. 2004; Reimer 2009).[8] This counterintuitive finding was initially chalked up to the fact that drivers tend to concentrate their gaze on the forward roadway when multitasking (e.g., Briggs et al. 2017; Engström et al. 2005; Harbluk et al. 2007; He et al. 2011; Horrey et al. 2006; McCarley et al. 2001; Recarte and Nunes 2000; Reimer 2009; Reimer et al. 2012; Strayer et al. 2017; Tsai et al. 2007; Victor et al. 2005). In fact, there is a tight coupling between where a driver looks and their steering inputs (Readinger et al. 2002; Rogers et al. 2005; Wilson et al. 2008).

To test the hypothesis that increasing cognitive load leads to a concentration of gaze that results in reduced lane position variability, Cooper et al. (2013) independently manipulated eye movements and cognitive load. They found that eye movements had only a modest impact on lane position variability, whereas the cognitive load had a much greater impact. Cognitive load reduced variability in lane position even when the eyes were not concentrated on the forward roadway. These data are in line with Logan and Crump's (2009) hierarchical control theory that suggests that complex skills, such as driving, are governed by an "outer loop" that is dependent on limited-capacity attention and an "inner loop" that is more automatic and does not place demands on attention. In fact, paying attention to the inner loop interferes with performance, whereas attention is necessary for efficient outer loop performance. The distinction between outer and inner loops has been applied to typing, golfing, soccer, and playing a musical instrument where paying attention to keystrokes on a typewriter, swings of the golf club, footwork when dribbling a soccer ball, or fingering on a guitar disrupts skilled performance (e.g., Beilock et al. 2002; Logan and Crump 2009).

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[8] The improved lane keeping observed under higher levels of cognitive load is not found with higher levels of visual load. This fact makes it easy to differentiate a cognitively distracted driver from a visually distracted driver. In the latter case, higher visual load (e.g., reading a text message) impairs lane keeping behavior.

Hierarchical control theory predicts that paying attention to the outer loop should improve the attention-demanding components of driving, whereas attending to the inner loop should degrade the more automatic components of driving. Conversely, because multitasking diverts attention from driving, it should cause outer loop components to suffer and inner loop components to prosper. Medeiros-Ward et al. (2014) examined lane maintenance while factorially manipulating secondary task load and driving predictability. When driving became less predictable due to wind gusts, more attention was required to maintain lane position. Under this circumstance, performing a cognitively demanding secondary task degraded lane maintenance. However, with predictable driving (i.e., no wind gusts), performing a cognitively demanding secondary task actually improved lane maintenance. Essentially, multitasking has differential effects on outer and inner loop performance. Counterintuitively, multitasking can actually improve the more automated components of driving that are not dependent on limited-capacity attention.

7 Neural Basis for Individual Differences in Multitasking

In the process of examining individual differences in multitasking ability, a handful of individuals were identified who, quite unexpectedly, showed no decrements when combining driving in a simulator with conversing on a hands-free cell phone (Watson and Strayer 2010). Measures of driving performance (i.e., brake reaction time and following distance) and performance on a cognitively demanding conversation surrogate (i.e., an auditory/vocal version of the OSPAN Task with measures of math accuracy and memory recall) were either unchanged or actually improved when the two tasks were combined. Approximately 2.5% of participants tested in this dual-task combination were identified as *Supertaskers*, individuals with extraordinary multitasking ability. Watson and Strayer (2010) used Monte Carlo simulations to show that this pattern of dual-task performance could not be explained by chance variation.

Subsequent testing of these Supertaskers used fMRI measures obtained while participants performed a very challenging version of the dual N-back task (Jaeggi et al. 2007). Compared to age, gender, and working memory capacity matched controls, Supertaskers exhibited patterns of greater neural efficiency while performing the dual N-back task (Medeiros-Ward et al. 2015)[9]. When multitasking, Supertaskers brains were characterized by more efficient recruitment of the anterior cingulate cortex (ACC, Broadmann areas 24 and 32) and the frontopolar prefrontal cortex

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[9] The dual n-back task involves the performance of two functionally independent tasks. This dual-task combination involved the simultaneous presentation of visual/spatial and auditory/verbal stimuli. Participants processed both modalities independently and responded if the visual/spatial or auditory/verbal stimuli matched the stimulus N-times back (e.g., 1-, 2-, or 3-back). The vast majority find the dual n-back task to be impossibly hard; however, Supertaskers perform the task at near perfect levels of performance.

(FP-PFC, Broadmann area 10). While performing this challenging multitasking combination, Supertaskers performed better than the controls despite these brain regions being significantly *less* metabolically active, as measured by the Blood-Oxygen-Level-Dependent (BOLD) signal.

The ACC and FP-PFC brain regions of the prefrontal cortex play an important role in cognitive control and appear to be critical for efficient multitasking. The ACC is a subcortical structure that is involved in attentional control (Bush et al. 2000) and is considered to be an integrative hub involved in prioritizing what information in the environment to attend to and what information to ignore (Holroyd and Coles 2002). The ACC is also thought to play a prominent role in conflict monitoring (Botvinick (2007) and the detection of errant behavior (Gehring and Fencsik 2001; Gehring et al. 1993). The FP-PFC is an area of the brain found exclusively in primates that is thought to play an important role in managing competing secondary-task goals and switching between them (Braver and Bongiolatti 2002; Mansouri et al. 2017). Patients with damage to this part of the brain often have particular difficulty with multitasking (Burgess et al. 2000; Dreher et al. 2008).

Coming full circle, the fMRI data suggest that the prefrontal cortex is actively engaged when humans attempt to concurrently perform multiple tasks, such as driving and conversing on a hands-free cell phone. The fMRI BOLD signal shows high levels of metabolic activity in the ACC and FP-PFC for 97.5% of participants who are not Supertaskers. We suggest that the ACC plays a critical role in integrating and prioritizing the primary task (i.e., driving) and secondary-task information and that the FP-PFC helps manage the task goals and switch between the driving task and any concurrent secondary task.

A specialized version of the dual N-back task used to identify Supertaskers is available online at www.supertasker.org. Like Jaeggi et al.'s (2007) task, the online version presents visual and auditory streams of information and the participant must process the information independently to make a classification.[10] The cover story for the Supertasker test is that participants act as a bouncer at a nightclub and only let "cool people" into the club. Cool people do not try to enter recently used doors or use recently used passwords (i.e., the doors and passwords are the visual and auditory streams of information that form the backbone of the N-back task). After completing the Supertasker test, participants are given a score based on the formal measures of capacity (e.g., Heathcote et al. 2015). Try the test and let us know how you do.

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[10] One of the volunteers who received a perfect score in the online version of the Supertasker task contacted the software developers to inquire about his perfect score (he actually received a perfect score twice, once in the initial test and again on a subsequent retest). This individual reported that he is considered to be one of the top sight-readers in the classical piano industry. Another volunteer who was rated as a Supertasker was on the British Olympic team. We believe that it is likely that Supertaskers, who represent approximately 2.5% of the population, excel at all sorts of real-world tasks that involve high levels of multitasking.

8 Who Multitasks and Why?

On the other end of the ability continuum are individuals who persist in multitasking even though they are bad at it. Sanbonmatsu et al. (2013) examined the relationship between *self-perceived* multitasking ability, impulsivity, sensation-seeking, and *actual* multitasking ability. These authors obtained self-reported measures of cell phone usage while driving along with measures from the media multitasking inventory (Ophir et al. 2009). Participants also performed a computerized version of the OSPAN task (Unsworth et al. 2005) and completed personality inventories assessing impulsivity, sensation-seeking, and self-perceived multitasking ability.

Chronic multitaskers were found to be the least capable of multitasking. This is a remarkable finding because people often frequent activities in which they excel. In fact, those with lower executive control, as measured by the OSPAN task, were more likely to use their cell phone while driving and they also scored higher on measures of impulsivity and sensation-seeking. These individuals also scored high on media multitasking, a pattern that is consistent with previous research by Ophir et al. (2009). There was a positive correlation between an individual's self-perception of their multitasking ability and their actual usage of a cell phone while driving. In fact, 70% of those sampled believed that their ability to multitask was better than average, a statistical impossibility. This shows a disconnect between *perceived* multitasking ability and *actual* multitasking ability. Drivers who had lower working memory capacity and scored higher in attentional impulsivity and sensation-seeking, particularly those scoring high in the disinhibition component of sensation-seeking, were more likely to use their cell phone while driving.

One paradoxical finding is that the vast majority of the public favor legislation that would prohibit using a cell phone while driving. For example, a survey by the AAA Foundation for Traffic Safety (2013) found that 88.6% of respondents felt that cell phone use while driving was a very serious or serious threat to their personal safety. This survey also found that 70% of respondents supported law that would restrict hand-held cell phone use while driving and 45% supported a total ban on cell phone use while driving. Nevertheless, recent sensor data obtained from over 3 million motorists found that drivers were using their phone on 88% of their trips (Zendrive 2017). Moreover, at any given daylight moment, 9.7% of the public can be seen using their cell phone to talk or text while operating their vehicle (DOT 2019).

Sanbonmatsu et al. (2016a) examined the disconnect between support for legislation restricting cell phone use while driving (62% in their sample) and actual use of a cell phone while driving (78% in their sample). The correlational study found that motorists perceived the benefits of *their* usage to outweigh the perceived risks to them of crashing. Participants were overconfident in their own ability to multitask relative to others. However, they did not believe that *others* were capable of driving safely while talking on a cell phone. That is, they considered *others*' use as a threat to *their* safety. Moreover, the survey found that motorists did not perceive a benefit from others' usage, whereas they felt that they did benefit from their own usage.

This hypocrisy in the form of “do as I say, not as I do” demonstrates that people want the laws to apply to other distracted drivers.

As discussed earlier in this chapter, multitasking motorists often fail to notice things in the driving environment (i.e., they have poor situation awareness). Supporting this notion, a study by Sanbonmatsu et al. (2016b) found that multitasking diminished motorist’s self-awareness of their impaired driving. The decrease in performance monitoring caused participants to be less aware of their actual driving errors, an unfortunate consequence of inattentional blindness. Consequently, motorists may persist in the belief that they can multitask while driving. These authors note that the multitasking “drivers who made the most errors exhibited a pattern similar to the fictional character Mr. Magoo, who was blithely unaware of his driving impairments” (p. 622).

Taken together, the studies by Sanbonmatsu et al. (2013, 2016a, b) paint an alarming picture of the multitasking motorist. Those most likely to multitasking while driving have lower working memory capacity, score higher in impulsivity and sensation-seeking, are overconfident in their abilities, and are often blind to the errors that they do make. Nevertheless, they engaged in this multitasking behavior because they feel that the benefits outweighed the risks, yet they did not feel the same about other multitasking motorists.

9 Multitasking and Device Addiction[11]

An incoming call or text is often a rewarding social stimulus that is difficult for motorists to ignore because it stimulates the dopaminergic reward network in the brain. The dopaminergic mesolimbic system is composed of the ventral tegmental area (VTA), the amygdala, and the nucleus accumbens (NAc). This primitive brain network helps the organism to pay attention to the features of a rewarding experience so that it can be repeated (Banich 2004). The reward circuits exert powerful control over behavior. The prefrontal cortex provides top-down control of the subcortical brain regions associated with reward and emotion regulation (Heatherton and Wagner 2011; Uncapher et al. 2017). Self-regulatory failure occurs if the balance is tipped in favor of the reward circuits due to the strength of a stimulus (e.g.,

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[11] It is hotly debated whether smartphone use rises to the level of a “true” behavioral addiction, similar to a gambling disorder (e.g., Griffiths 2013; Roberts 2016). The question of whether smartphone use is a behavioral addiction conforming to the Diagnostic and Statistical Manual for Mental Disorders (DSM-5) criteria or just “problematic smartphone use” that is “distinct from other addictions that merely use the smartphone as a medium” (Yu and Sussman 2020, p. 422) is beyond the scope of this chapter. However, a comprehensive review of 108 peer-reviewed articles generally supports the conclusion that smartphone addiction is a genuine addictive disorder (Yu and Sussman 2020).

a rewarding text message) or a failure to exert executive control (e.g., due to fatigue associated with excessive multitasking).

Like the ringing bell for Ivan Pavlov's classically conditioned dogs, the driver has been classically conditioned to *their* ringing cell phone. When their phone rings (i.e., the conditioned stimulus), the driver may reflexively answer the call and connect to their social network. The dopamine reward-learning network has been implicated in this sort of cue-reward pairing (Pan et al. 2005). Whereas a driver's cell phone is a rewarding conditioned stimulus, people often find other ring tones aversive and annoying. That is, a ring tone is not an inherently rewarding stimulus. The ring tone must be paired with a user's own smartphone for it to acquire this property.

Motorists may acknowledge that they should not use their smartphones while driving, yet they do it anyway. Using the smartphone to interact with a motorist's social network is a very powerful and rewarding stimulus. In fact, the author DS knows several people who have lost loved ones in a distracted driving crash. These individuals, who were not in the vehicle when it crashed, now lock their smartphones in the trunk so that they are not tempted to use their devices while driving (an example of *proactive* self-regulation).[12] They report that if the smartphone is in the car, they are drawn to it. Because driving places demands on the prefrontal attentional network, self-regulatory failure often occurs when the motorist's phone rings.

Based on estimated crash risk, Strayer (2017) developed a 6-item scale to determine the level of risk associated with using a smartphone while driving. Points are assigned based on whether a driver engaged in the activity while driving in the last week. A score between 1 and 3 was considered to be a moderate level of risk, a score between 4 and 6 would be considered a high level of risk, and a score greater than 6 would be considered an extreme level of risk. It is noteworthy that the National Transportation Safety Board (NTSB 2011) and the National Safety Council (NSC 2010) consider that driving is compromised if the obtained score is greater than 0.

- Accepting a phone call while driving (1 point)
- Placing a call (including dialing) while driving (2 points)
- Reading a textual message while stopped at a traffic light (1 point)
- Sending a textual message while stopped at a traffic light (1 point)
- Reading a textual message while driving (2 points)
- Sending a textual message while driving (2 points)

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[12] Strayer and Cooper (2015) distinguished between proactive and reactive self-regulation of smartphone use while driving. Drivers may *proactively* self-regulate their multitasking activities to periods when they are stopped at a traffic light (e.g., Huth et al. 2015), even though the persistent costs described earlier make this less than an optimal strategy. Drivers may also attempt to *reactively* self-regulate their multitasking activity to periods when driving demands and consequences for distraction are higher (e.g., when driving in a work or school zone); however, the inattentional blindness caused by such activities often renders this strategy ineffective.

10 Attention and Vehicle Automation

The recent introduction of automated vehicles poses new attentional challenges for motorists. The Society of Automotive Engineers categorizes six levels of automation in vehicles, from Level 0, meaning no automation, to Level 5, meaning full automation (SAE 2016). Presently, vehicles with Level-2 automation, henceforth referred to as semiautomated vehicles, are publicly available and are equipped with systems that employ lateral and longitudinal control. These vehicles enable adaptive cruise control and lane-centering technology to be engaged simultaneously. The technology is not perfect, and in accordance with the SAE guidelines for semiautomated systems, drivers are required to remain vigilant and be able to take back manual control of the vehicle at any time.

In semiautomated vehicles, the primary task of the driver changes. Rather than being in full control of the vehicle, the driver instead takes on the role of passively monitoring the vehicle for rare technological failures. The driver must also monitor the environment for instances that the automated system is not designed to handle. Even though there is a shift from the active controller to the passive monitor, the demands illustrated in the SPIDER model still exist (e.g., scanning, predicting, identifying, deciding, executing responses) and the driver must maintain situation awareness at all times. However, researchers are still trying to understand how this new role of monitoring affects the allocation of attention to the primary driving task and willingness to engage in secondary tasks (i.e., multitask).[13]

One concern regarding the automation of vehicles is that passive monitoring might make it difficult for motorists to maintain optimal levels of arousal, which can lead to fatigue and impairments in situation awareness. Some believe automation might impair situation awareness due to changes in vigilance and complacency (Endsley and Kiris 1995), while others believe automation may potentially improve situation awareness by decreasing the workload placed on the driver (Billings 1991). In terms of multitasking, researchers have found that drivers who are performing a secondary task take longer to take back manual control of the vehicle if the automated features deactivate (Vogelpohl et al. 2018).

The Yerkes–Dodson model describes the relationship between arousal, attention, and task performance (Yerkes and Dodson 1908). Optimal levels of performance on a task occur when there is a moderate level of arousal, as depicted by the mid-point of the inversed-U shaped function (Cohen 2011, p. 2737; Yerkes and Dodson 1908). Attention affects arousal levels such that high demands can increase arousal to detrimental levels, resulting in poor task performance (Derakshan and Eysenck 2009). For example, driving that demands high and sustained attention can increase stress and lead to detriments in driving performance (Langner and Eickhoff 2013). In

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[13] In the future, when Level-5 automation becomes commonly available, the safety-related concerns regarding multitasking motorists becomes moot. Until that time however, multitasking is likely to compete with a driver's ability to monitor the semi-automated vehicle and maintain good situation awareness.

terms of arousal, some researchers have found that over-arousal when monitoring semiautomated vehicles can lead to faster onset of fatigue and decrements in vigilance (Greenlee et al. 2019). Others have found that under-arousal might also lead to fatigue and disengagement from the environment (Manly et al. 1999, p. 661). The degree to which driving semiautomated vehicles may lead to over- or under-arousal is not well understood.

Physiological measures can be used to assess motorist arousal and engagement with the driving environment in real-time (see Lohani et al. 2019). For example, electroencephalography (EEG) measures the summated electrical activity in the brain from electrodes on the scalp. It is noninvasive and mobile and allows for direct recording of neural activity in response to the demands of an environment. EEG can be decomposed into various frequency bands (Delta ~0.5–4 Hz, Theta ~4–8 Hz, Alpha ~8–12 Hz, and Beta ~12–30 Hz) using Fourier analysis (Cohen 2014). These frequency bands are studied in relation to different cognitive functions. For example, alpha power in parietal regions of the brain is reflective of visual attention, such that higher alpha power indicates lower visual engagement with the environment and lower alpha power is indicative of higher visual engagement (Bowman et al. 2017; Foxe and Snyder 2011). Alpha power is greatest when an individual's eyes are closed (Berger 1933). Additionally, fatigue and under-arousal have been shown to increase alpha power (Chuang et al. 2018; Käthner et al. 2014), while an increase in cognitive workload and arousal has shown to decrease alpha power (Mun et al. 2017). Therefore, power in the alpha frequency band is a useful metric to assess visual engagement and arousal while driving.

Strayer et al. (2020) recorded EEG when motorists operated Level-0 (no automation) and Level-2 (semiautomation) vehicles on a network of interstate highways. It was hypothesized that if driving semiautomated vehicles leads to a decrease in arousal and task engagement, there would be an increase in alpha power, whereas if driving semiautomated vehicles leads to an increase in arousal and task engagement, there would be a decrease in alpha power. Contrary to popular concern about threats of fatigue and disengagement associated with automated vehicles, Strayer et al. (2020) found a slight *decrease* in alpha power with semiautomated driving (compared to manual driving). This is consistent with the SAE guidelines that drivers must remain engaged with the primary driving task even when driving in semiautomated mode.

Presently, it is unknown how the development of trust in semiautomated vehicles over the long haul might affect attention (and driver's situation awareness), arousal, and the willingness to multitask. It is possible that as a driver becomes more comfortable with the technology, they may become more likely to disengage from the environment, or "zone out". As automated technology continues to develop, it will become increasingly important to assess driver arousal and attention with sensitive, real-time measures.

11 Red Line of Workload

Finally, it is important to establish a red line of workload (Grier et al. 2008), a level at which the task demands exceed the capacity of an individual and where performance degrades to unacceptable and/or unsafe levels. In the context of driving, multitasking activities that cross the red line increase the risk of crashes and fatalities (WHO 2011). Strayer et al. (2019) compared a driver's workload when performing four different task types. These task types are commonly available in new vehicles via the embedded in-vehicle infotainment system (IVIS). The four task types were (a) *audio entertainment* (e.g., selecting different sources of music), (b) *calling and dialing* (e.g., placing an outgoing call from a contact list or dialing a number), (c) *text messaging* (e.g., listening to short text messages and replying from a list of predetermined messages), and (d) *navigation* (e.g., initiating GPS route guidance to different locations). These task types were compared to the single-task (driving) baseline and to a high-demand benchmark (i.e., the red line of workload).

The red line of workload was established by applying the NHTSA's (2013) upper limit for total task time (e.g., 24 seconds, using a visual occlusion testing procedure). The general principle was that IVIS interactions should be performed in 24 seconds or less when paired with the task of operating a moving motor vehicle. The red line of workload was also calibrated by having drivers concurrently perform a cognitively demanding auditory N-back task (Mehleret al. 2011) or a visually demanding visual/manual search task (i.e., the SuRT task, ISO TS 14198 2012). The red line of workload shown in Fig. 5 reflects the driver's workload when they concurrently performed either the N-back or SuRT task (i.e., the red line represents the average workload for the N-back and SuRT tasks, each done separately, scaled by 24 seconds, see Strayer et al. 2019 for additional details).

The on-road evaluation of the IVIS interactions performed by Strayer et al. (2019) found that the audio entertainment and calling and dialing features were significantly below the red line of workload (approaching but not exceeding the red

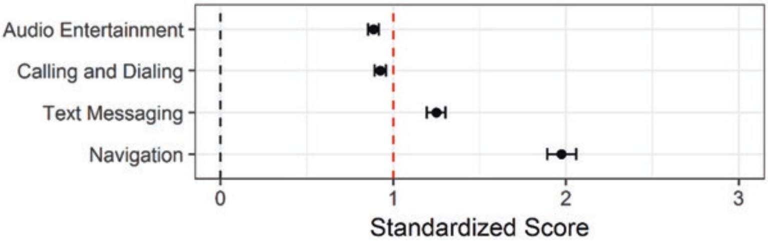

Fig. 5 The overall demand as a function of secondary-task type from Strayer et al. (2019). The dashed vertical black line represents workload in single-task driving, and the dashed vertical red line represents the "red line" of workload. Error bars represent 95% confidence intervals

line of workload). By comparison, both the text messaging and navigation task types significantly exceeded the high-demand baseline. Notably, the navigation task type was associated with *twice* the demand of the red line of workload. Given the observed high level of workload, it is not surprising that NHTSA's (2013) visual-manual guidelines recommend against enabling this feature when the vehicle is in motion. Unfortunately, these guidelines are voluntary (i.e., left to the discretion of auto manufacturer), and it was enabled in 40% of the test vehicles when participants were driving.

12 Summary

Multitasking in the automobile is ubiquitous. This concurrent performance of a secondary task that is unrelated to driving has been shown to divert attention from the primary task of operating a motor vehicle. Multitasking impairs SPIDER-related activities (e.g., scanning, predicting, identifying, deciding, executing responses) and compromises a motorist's situation awareness. There is considerable variability in the mental workload associated with different multitasking activities. Some concurrent tasks, like listening to the radio or audio book, have little impact on driver workload and driving performance. Tasks involving a conversation with another person impose a higher mental load than listening to the radio or audio book. Multitasking with more complex in-vehicle information systems (e.g., voice-based or multimodal visual, manual, and cognitive interactions) is associated with surprisingly high levels of driver workload and impairments to driving. When motorists terminate a multitasking operation, there is a persistence in distraction that lasts for at least 27 seconds. The secondary-task threads appear to be "impolite" and suggest that the information supporting the abandoned secondary task decays gradually from working memory. In part, impairments to driving from multitasking stem from crosstalk between two tasks that use similar or overlapping information that come into conflict. Indeed, not all conversations are equivalent, and language with different content recruits different neural hardware and produces different patterns of interference with driving. Counterintuitively, whereas multitasking clearly impairs higher-level cognition, some of the lower-level automated aspects of driving, such as maintaining lane position, may actually improve under cognitive load. Multitasking places heavy demands on the prefrontal cortex, particularly the frontopolar and anterior cingulate cortices. For most drivers, these brain regions show high levels of metabolic activity whilst multitasking. However, Supertaskers, thought to comprise about 2.5% of the population, are able to multitask at high levels without overloading these neural circuits. On the other end of the continuum are those who persist in multitasking and are bad at it. Intriguingly, individuals most likely to multitask while driving have lower working memory capacity, score higher in impulsivity and sensation-seeking, are overconfident in their abilities, and are often blind to the errors that they do make. These drivers also felt that the benefits of multitasking outweighed the risks; however, they did not feel the same about other multitasking motorists. There is evidence that many drivers suffer from problematic smartphone use, reflexively answering a call when the phone rings. Future advancements in vehicle automation may make the safety-related concern regarding multitasking motorists moot. Until that day, multitasking is likely to compete with a driver's ability to monitor the vehicle and maintain good situation awareness.

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Multitasking in Healthy Aging and Neurodegeneration: Experimental Findings and Health-Related Applications

Karen Z. H. Li and Rachel I. Downey

A central concern of healthy aging is the maintenance of functional capacity and avoidance of disability. The World Health Organization's International Classification of Functioning (ICF), Disability and Health (WHO 2002) is a useful framework in which to situate the present chapter on multitasking and health implications. According to the ICF, healthy functioning is multidetermined by factors such as the presence or absence of disease, and bodily functions and structures that include the integrity of cognitive, sensory, and motor systems. These factors impact the level of activity (e.g., execution of everyday tasks such as personal care, feeding, dressing) and participation in life situations (social engagement), which many would consider vital to one's quality of life. Added to this multifaceted definition of health is the dimension of aging and the progression of age-related diseases such as cognitive impairment (e.g., Alzheimer's disease [AD], mild cognitive impairment [MCI]). From a lifespan developmental perspective, it is also worth considering that each of these facets (bodily structure and function, disease, activity, participation, environment, personal) interact and may have increased interdependencies as a function of age-related decline and reduced reserve capacities (Baltes and Lindenberger 1997; Cabeza et al. 2018; Park and Reuter-Lorenz 2009).

Activity and engagement are central components of the WHO model of functioning, disability, and health (WHO 2002). As such, in the current chapter, we focus our discussion on health-relevant multitasking processes based on the view that multitasking efficiency plays a vital role in independent living. Executive functions, such as task switching, dividing attention, and inhibition, have been linked to standard markers of functional status and independence (e.g., Hall et al. 2011; Heyl and Wahl 2012). For example, a geriatric assessment tool commonly used in decisions to transition seniors from independent living to care facilities is Katz's Activities of Daily Living (ADL) clinical checklist (Katz et al. 1963). The ADL scale includes

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activities such as dressing, transferring from a chair/bed, walking, climbing stairs, and self-feeding. More cognitively intensive is the Instrumental ADL (IADL; Lawton and Brody 1969), which includes shopping, managing finances, and driving. ADL and IADL scores are predicted by neuropsychological measures of task switching, such as the Trail Making Test Form B (TMT-B; Cahn-Weiner et al. 2002). The baseline TMT Form A requires one to rapidly connect the numbered dots on a page in ascending order, whereas TMT-B requires alternation between ascending letter and number series (Reitan 1992). Notably, Arbuthnott and Frank (2000) validated the TMT-B as an index of executive functioning, showing a strong relationship between TMT-B and task alternation latencies in an experimental set switching paradigm. TMT-B has also predicted mortality rates in older adults (Johnson et al. 2007). Performance-based measures of ADL correlate with TMT-B in combination with the Wisconson Card-Sorting Task, another measure of switching and cognitive flexibility (Bell-McGinty et al. 2002). Together, the clinical literature suggests that processes that support multitasking (e.g., switching) play an important role in the functional independence of older adults.

To understand the ways in which everyday activities, such as driving, cooking, and communication, are accomplished or hindered with aging and neurodegeneration, it is important to briefly review the literature on aging and cognitive multitasking processes, such as task alternation and divided attention. These classic experimental paradigms have been comprehensively reviewed in this volume (e.g., Janczyk & Fischer, Chap. 1; Johannsen & Krampe, Chap. 2; Koch & Kiesel, Chap. 3) and elsewhere (e.g., Koch et al. 2018; Kramer and Madden 2008; Verhaeghen 2011; Verhaeghen et al. 2003). Thus in this section we have opted to highlight the major conceptual issues and findings, leaving more space for the second section, in which we focus on multitasking during everyday motor performance (e.g., walking while talking, balancing while listening). The health implications of motor multitasking are clear, given the potentially life-threatening consequences of falls for older adults and the established association between motor and cognitive functioning with aging, with particular emphasis on executive control processes (e.g., Li and Lindenberger 2002; Seidler et al. 2010; Yogev-Seligmann et al. 2008). Each section begins with a brief mention of common assessment methods and coverage of key findings with respect to typical aging (aged 60+) in contrast to younger adult controls (aged 18–35 years) and to older adults with cognitive impairments and other neurodegenerative disorders.

1 Cognitive Multitasking and Aging

1.1 Task Switching and Aging

In the cognitive aging literature, task switching is assessed experimentally using two principle methods. In the alternating runs paradigm, the task sequences are predictable such as in the case of performing two trials of Task A, followed by two trials of Task B, then returning to two trials of Task A, and so on (AABB; e.g., Rogers and Monsell 1995). By contrast, in the task-cuing paradigm, the task sequences are unpredictable and the upcoming task is explicitly cued (e.g., Meiran 1996). Switching efficiency is assessed with two types of switching costs. First, "local" switch costs reflect the difference in average response time (RT) between task switches and task repetitions in a mixed block of trials, where A and B represent different task sets and the underlined letters denote the trials of interest for analysis (i.e., BBAB). This "local" switch cost is an indication of the executive processes associated with transitioning from one task set to the next. Second, the "global" switch cost, or mixing cost, is the difference in RT between trials in a mixed block (i.e., BBAB) in contrast to trials in a homogeneous task block (i.e., BBBB). Alternatively, one can isolate the nonswitch trials within mixed blocks (BBAB) and compare those to nonswitch trials within homogeneous blocks. The global switch cost is thought to reflect the extra memory load associated with maintaining and scheduling two task sets within a block.

Early investigations of young–old differences in task switching suggested that age-related differences in local switch costs were small to negligible (e.g., Botwinick et al. 1958; Brinley 1965) after accounting for age-related general slowing by computing proportional switch costs relative to response latencies in nonswitch trials. Kramer et al. (1999) noted that the early work commonly compared blocks of nonswitch trials against mixed blocks of switch trials, thus creating potential confounds of arousal and motivation between conditions. In response, Kramer et al. (1999) compared homogeneous nonswitch blocks against mixed blocks containing switch and nonswitch trials, enabling the distinction between global switch costs and local within-block switch costs. They found large age-group differences in global costs favoring the young adults and small to minimal effects of age in local switch costs. An important feature of their work was to examine the effects of extensive practice (over 1–4 sessions) on the age differences in switch costs. Across three experiments, it was found that the sizeable age-related differences in switch costs were significantly reduced after 1–2 sessions of practice, except in the case of very short preparatory response-stimulus intervals (200 ms) and when working memory demands were increased by eliminating cues and instructing participants to switch after every five trials.

Kray and Lindenberger (2000) conducted a comprehensive developmental investigation (age range of 20–80 years) of local and global switch costs using three classes of stimuli (digits, figures, words) across four sessions of practice. They extended the demands for internal monitoring by requiring participants to alternate between pairs of task sets in a predictable sequence (e.g., AABBAA…) without external cues. Like Kramer et al. (1999), they compared mixed and homogeneous blocks, deriving local and global switch cost scores across their continuous age sample. Preparation time was varied in terms of response stimulus intervals (RSI; 200 ms vs. 1200 ms) to examine the potential interacting effects of age, practice, and preparation time on local and global switch costs. In agreement with Kramer et al. (1999), age differences in global switch costs were more substantial than in local switch costs, and practice effectively eliminated age differences, particularly with more preparation time (see also Cepeda et al. 2001).

Mayr (2001) replicated and extended Kray and Lindenberger's (2000) findings using a cued switching paradigm with three tasks (form, color, size decisions) in order to examine age differences in backward inhibition of recently abandoned task sets (Mayr and Keele 2000) as a potential explanation for age differences in switching performance. In backward inhibition, also referred to as *n-2* repetition cost, a slowed response is expected when the task set associated with trial *n*-2 is repeated in trial *n* (e.g., AB<u>A</u> versus a control sequence CB<u>A</u>). The magnitude of the slowing is attributed to the efficiency of inhibition that is thought to occur during the switch to another task set. Assuming age-related inhibitory decline, one would expect older adults to exhibit less response slowing than younger adults on trials containing task sets that were recently abandoned and presumably inhibited to facilitate the transition to another task set. Mayr replicated Kray and Lindenberger's (2000) large age group effects in global switch costs and small group effects in local switch costs but did not find evidence of age-related deficits in backward inhibition. Li and Dupuis (2008) examined age differences in backward inhibition in the context of sequential action control (Li et al. 2000) using Hübner et al.'s (2003) flanker-based backward inhibition paradigm. Here, inhibitory efficiency is operationalized as a facilitation effect when a recently abandoned task set recurs in the form of to-be-ignored flanker stimuli, relative to trials in which this sequential relationship does not occur. Across three experiments with varying preparatory intervals and selection loads, young and older adults exhibited equivalent degrees of backward inhibition, suggesting that age differences in task switching efficiency are not attributable to this specific form of sequential (backward) inhibition.

Importantly, Mayr (2001) examined another source of age differences in global switch costs by manipulating the degree of overlap between stimuli and between responses of the competing task sets. Specifically, under conditions of high stimulus ambiguity and response set overlap, older adults showed larger global switch costs, presumably because of the greater updating and working memory (WM) demands imposed by the increased ambiguity (Mayr 2001). Mayr and Liebscher (2001) expanded on this interpretation using a variant of the task-switching paradigm in which a fade-out procedure was introduced part way through mixed blocks, indicating that one of the two task sets would no longer be relevant. The age difference in global switch costs persisted even after the WM demands were reduced in the fade-out phase, suggesting that age differences in global switch costs were not only due to WM maintenance difficulties but also due to a more general age-related decline in the selection of mental sets and downregulation of irrelevant sets.

Following on with the interpretation that age differences in global switch costs may be due to age-related difficulties in WM maintenance and coordination, Kray et al. (2002) examined local and global switching costs between age groups by increasing the number of task sets from 2 to 4, reasoning that the increased WM load would exacerbate the age-related switch costs. Age differences were found for global switch costs, but unlike other work, the age differences were only present for switch trials within the mixed blocks and not for nonswitch trials. Kray et al. (2002)

also did not find that age interacted with task set size, proposing that the presence of trial-by-trial cueing may have counteracted the potential increase in WM demands and reduced task selection uncertainty. More importantly and unlike previous work, with the increased WM load of 4 task sets, age differences were found in local switch costs, which were larger than the age effect for global switch costs. An explanation for the smaller age effects in global switch costs was that all trials were cued in the Kray et al. (2002) study, although Mayr (2001) found the more typical pattern of larger age differences in global than local switch costs with trial-by-trial cueing using three task sets.

These behavioral dissociations are echoed in functional neuroimaging studies showing, for example, that global switch costs are associated with the age-sensitive right anterior prefrontal cortex, whereas local switch costs are associated with nonfrontal regions (e.g., the right superior parietal cortex; Braver et al. 2003; see also Nashiro et al. 2018). Using ERP measures, Goffaux et al. (2006) found that older adults with high working memory performed similarly to younger adults on mixed-task trials but had greater neuroelectric activity at frontolateral sites, suggesting the recruitment of additional neural resources, which may or may not be compensatory (cf. Nashiro et al. 2018). In contrast, older adults with low working memory showed activation on all trials, even those in single-task blocks, suggesting that they failed to maintain the task set in working memory and used the cue on every trial to guide performance. A recent comprehensive review of aging, task switching, and ERP (Gajewski et al. 2018) considers evidence for differing components of task switching (task preparation, implementation, response monitoring) and suggests multiple age-related processing changes (updating, interference processing during response selection), or more generally, age-related deficits in proactive and reactive control mechanisms based on the Dual Mechanisms of Control framework of Braver (Braver et al. 2007).

A smaller body of research examines switching efficiency in the context of clinically defined cognitive impairments. MCI is defined as memory impairment without loss of functional capacity for daily activities (Jessen et al. 2014). Cognitive flexibility, as measured with TMT-B or TMT form B minus A completion times, discriminated reliably between age-matched healthy controls and multi-domain MCI patients, who may exhibit deficits in inhibitory control, cognitive flexibility, language, working memory, and constructive praxis (Gonçalves et al. 2019). Similar group differences were found in a comparison of age-matched controls and persons with mild to moderate Alzheimer's type dementia (Coubard et al. 2011) using TMT Form B-A, and the switch error rate for Spector and Biederman's (1976) Plus-Minus Test, in which participants add three to random numbers in List 1, subtract three in List 2, and alternate between addition and subtraction in List 3. TMT-B has been proposed as a clinically meaningful tool to distinguish between cognitively impaired and unimpaired individuals (Ashendorf et al. 2008).

Of note is a larger experimental study using mixed and nonswitch blocks to compare local and global switch costs across young, middle-aged, older, and very mild AD groups (Huff et al. 2015). Notably, local switch costs were largest for young adults and decreased as a function of age and cognitive impairment. Conversely, global switch costs increased as a function of age and then decreased slightly for the mild AD group. A similar dissociation between global and local switch costs was found by Belleville et al. (2008) using a spatial switching task, although their AD group also exhibited greater local switch costs than the healthy controls, potentially due to a difference in impairment severity across studies. Velichovsky et al. (2020) found that MCI patients had disproportionately large local switch costs relative to age-matched controls using the Rogers and Monsell (1995) experimental procedure (see also Sinai et al. 2010).

In sum, the extant work on aging and task switching efficiency suggests that age-related reductions in WM capacity account for the commonly observed age effects in global switching costs and that these age differences are reduceable although not completely eliminated by training. The memory deficits associated with AD and MCI exacerbate these global switch costs. By contrast, age-related differences in local switch costs are small to null in most cases, unless the task conditions impose larger memory requirements or if the memory deficits are more severe. The evidence for exacerbated local switch costs in MCI patients is mixed at present, likely due to heterogeneity among MCI sub-types (Sinai et al. 2010) and test methods. Wasylyshyn et al.'s (2011) quantitative meta-analysis of task switching and typical aging confirmed these differential age effects for global versus local switch costs. Meta-regression analyses further revealed that global switch costs are attributable to the additional processing stage required to hold two task sets in mind in comparison to one task set, whereas the magnitude of local switch costs is attributable to generalized slowing. The observational studies of functional capacity identify task switching, or cognitive flexibility, as a specific executive function associated with ADL and IADL status.

1.2 Dividing Attention and Aging

A second area of aging and multitasking work focuses on experiments of divided attention or dual-tasking. Based upon early models of cognition and working memory (e.g., Baddeley 1986), dual-task and aging research was motivated by the premise that observations of performance reductions arising from added cognitive load (i.e., secondary or concurrent task requirements) indicate some shared or overlapping processing requirements (Kahneman 1973; Kinsbourne 1981; cf. Navon and Gopher 1979). Divided attention tests require the concurrent performance of two cognitive tasks, which may or may not share common characteristics at the stimulus, processing, or response stages. Divided attention proficiency is commonly measured in experimental designs by comparing component task performance (i.e., single-task/full attention conditions) to dual-task performance (divided attention conditions). Task costs are typically expressed either as absolute costs (e.g., dual-task minus single-task) or proportional costs (e.g., [dual minus single-task]/single-task), the latter being preferable to correct for age group differences in baseline single-task performance levels.

The divided attention, or dual-task, paradigm held early appeal as a way to test general resource reduction accounts of aging and memory performance (Craik 1983; Craik and Byrd 1982; Welford 1977). Early studies that paired simple memory or perceptual tasks (e.g., tone detection plus reading; dichotic digit memory) led to mixed support for the prediction that older adults should exhibit greater dual-task costs than younger adults due to reduced resource capacity (e.g., Baron and Mattila 1989; Salthouse et al. 1984; Somberg and Salthouse 1982; Tun 1989; Wright 1981).

In a series of studies by Craik and colleagues, the resource reduction view was tested by varying the component task requirements (e.g., memory load) during a sentence processing task (Gick et al. 1988; Morris et al. 1990). Across several experiments, dual-task costs were significant but were not disproportionately greater for older adults than for younger adults (Gick et al. 1988; Morris et al. 1990). This shared-resource approach was further elaborated by distinguishing divided attention effects during memory encoding versus retrieval (e.g., Anderson 1999; Anderson et al. 1998; Fernandes and Moscovitch 2000; Park et al. 1989). The majority of these studies show significant overall costs to memory performance when dividing attention at encoding and minimal costs at retrieval. Notably, the magnitude of dual-task costs appears age-equivalent at the encoding stage (Anderson et al. 1998; Baddeley et al. 1986) and somewhat mixed at the retrieval stage (e.g., Park et al. 1989; cf. Fernandes and Moscovitch 2003). Functional neuroimaging techniques reveal that the age-equivalence in behavioral dual-task costs may arise from patterns of compensatory activation in older adults (e.g., Fernandes et al. 2006). Overall, varying degrees of structural interference within dual-task pairings and varying demands for truly simultaneous processing have produced mixed findings with respect to age differences in divided attention performance.

An important issue in this field is whether age-related differences in dividing attention are due to a specific age-related deficit in dual-tasking or a common-cause factor such as general slowing (e.g., Salthouse 1996). The latter account assumes that simultaneous task performance increases overall complexity and that age-related increases in dual-task costs arise because each additional processing step (i.e., complexity increment) should compound the effects of slowing. McDowd and Craik (1988) examined the complexity perspective using concurrent auditory and visual tasks with varying levels of task complexity. They found reliably greater dual-task costs in older than younger adults, which were magnified with increased task complexity. To test the complexity hypothesis, they used Brinley plot analyses (plotting the young group latency data against the older adults' data for each complexity condition) to show that the same linear function captured both the full attention and divided attention condition data. Finding one linear function supports the view that age-related increases in dual-task costs could be accounted for by a simple slowing factor.

Kramer et al. (1995) examined the general slowing-specific age deficit issue with a training approach, reasoning that if there were specific age deficits in dual-task coordination, training should strengthen this task coordination ability (i.e., differentially boosting dual-task performance) and should not simply strengthen or automatize the component task processes. Furthermore, the training should transfer to other dual-task combinations (Bherer et al. 2005, 2008; Kramer et al. 1995; Lussier et al. 2012, 2017). Also, following the specific age deficit view, participants trained with a variable priority training schedule (block-wise variation of task emphasis) should exhibit greater dual-task improvements and transfer to untrained dual-task combinations compared to those receiving fixed priority training (equal task emphasis for all blocks), but training format should not affect benefits seen in the component tasks. Across numerous studies, training benefits were greater for dual-task conditions than for single component tasks and variable priority training was particularly advantageous for improving dual-task performance in the trained and untrained task combinations (Kramer et al. 1995; Lussier et al. 2017). Together, these results support the specific age deficit viewpoint over the general complexity approach.

Taking into consideration a variety of dual-task pairings, Verhaeghen et al. (2003) examined over 30 age-comparative dual-task data sets to examine if age differences in dual-task performances remain after accounting for general cognitive slowing. Brinley analyses indicated that older adults require roughly twice the processing time of younger adults to perform under dual-task conditions. Unlike McDowd and Craik (1988), Verhaeghen's meta-analysis showed separate linear functions for single- and dual-task performance conditions, suggesting that a separate factor above and beyond general slowing is driving the age-related differences in dividing attention. A subsequent examination of aging and multiple executive control functions (selective attention, task shifting, dividing attention) found that only tasks involving divided attention (dual-task coordination and global task switching) yielded evidence of specific age-related deficits beyond simple cognitive slowing (Verhaeghen 2011).

An important determinant of age-related differences in divided attention performance is the degree of processing or response overlap between component tasks, in that increasing similarity between tasks leads to greater interference and dual-task cost (e.g., Fernandes and Moscovitch 2000; Li 1999; Naveh-Benjamin et al. 2005). To further pinpoint the locus of age differences in dual-tasking, researchers have used the Psychological Refractory Period (PRP) paradigm (Welford 1952) to discern the stage of processing at which age differences in dual-task performances are the greatest (input, processing, response). Briefly, the PRP paradigm entails the presentation of Task 1 and Task 2 with a variable stimulus onset asynchrony (SOA) and observing a slowed Task 2 response when a processing bottleneck is encountered (see Koch et al. 2018; Pashler 1994; Janczyk & Fischer, Chap. 1, this volume).

In two experiments involving tone discrimination and visual dot location tasks, Allen et al. (1998) showed that older adults had a larger PRP effect than young adults. However, older adults also exhibited a strategy difference by withholding their Task 1 response until the Task 2 response was prepared (see also Glass et al. 2000). Experimental manipulations of stimulus and response characteristics have led to differing views on the nature of the age-related differences, such as cautiousness (Glass et al. 2000), interference at the input stage (Hartley et al. 2011; Hein and Schubert 2004), or interference at the response stage (Hartley 2001; Hartley and Little 1999). On balance, the available data show that older adults exhibit a greater time-sharing decrement than younger adults, even after extensive training or removal of structural interference (Hartley and Maquestiaux 2007; Maquestiaux et al. 2010).

Coordination ability is considered a key function of the central executive component of working memory (Baddeley et al. 1986; Della Sala et al. 1995; Logie et al. 2004). To study coordination costs separately from other sources of dual-task interference such as input or output similarity, Baddeley et al. undertook a series of studies comparing healthy younger and older adults and cognitively impaired older adults. Using a simple digit span task paired with a visuomotor tracking task, they found a specific dual-task impairment in AD patients but little difference between healthy older and younger adults (Baddeley et al. 1986; Della Sala et al. 1995; Logie et al. 2004) or between MCI patients and healthy age-matched controls (Foley et al. 2011; Dannhauser et al. 2005; c.f. Pettersson et al. 2005). This pattern remains robust even after individually equating single-task difficulty levels and after extensive practice (Foley et al. 2015). Together, studies using this approach suggest that dual-tasking may be used as a clinical tool to distinguish Alzheimer's type dementia (Della Sala et al. 2010).

In sum, the substantial body of research on aging and cognitive dual-tasking or divided attention suggests that cognitive multiple task coordination ability is reliably age-sensitive. However, the dual-task training studies indicate that younger and older adults are equally able to benefit from training and that older adults may benefit from variable priority training (i.e., the flexible allocation of attention between two tasks) even more than young adults. Examination of older adults with cognitive impairments reveals a specific dual-tasking deficit in AD patients with little improvement after extensive practice. Together, the evidence on aging and dual-task performance favors the view of a specific deficit in task coordination that is not accounted for by general processing speed changes or by performance on the component tasks alone.

1.3 Ecological Approaches to Aging and Cognitive Multitasking

A subset of the literature on aging and cognitive multitasking takes a more ecological perspective in considering simulations of work-based or everyday scenarios relevant to older adults. For example, Craik and Bialystok (2006) considered a computerized simulation of cooking breakfast that requires the monitoring of multiple cooking times along with a concurrent table setting task. Across multiple measures of task management, age-related declines in cooking task performance were observed. These observed declines were moderated by bilingual language experience, which is interpreted as a potential source of cognitive reserve that mitigates age-related declines in executive functions. Similar age-related declines have been observed in computer-simulated work settings that require concurrent monitoring of multiple displays in addition to memory or arithmetic tasks (Salthouse et al. 1996;

Todorov et al. 2014). These synthetic work studies show older adults to de-emphasize one or more of the particularly challenging tasks rather than apply equal effort to all tasks. The age differences have been attributed to reduced processing speed (Salthouse et al. 1996) or declines in executive functions, working memory, and specific visuospatial abilities (Hambrick et al. 2010; Todorov et al. 2014).

Driving is another important everyday activity that has been conceptualized as a divided attention situation. For example, younger and older adults are assessed on typical driving functions (braking, car following) either singly or while concurrently performing a secondary task such as sign reading (McPhee et al. 2004), remembering roadside details (Wechsler et al. 2018), or conversing on a cell phone (Strayer and Drews 2004). In all cases, the attentional control and dual-task demands were more detrimental to the driving performance of older adults than younger adults. Notably, compared to younger drivers, older drivers report less frequent multitasking behaviors while driving (e.g., phone use, talking, eating, drinking), although this age difference is moderated by self-reported executive functioning such that those lower in executive control report more distracted driving behaviors (Pope et al. 2017). In addition to the self-reported data, in objectively assessed driving experiments, relative to younger drivers, older drivers display less willingness to answer incoming calls as a function of increasingly challenging road conditions and report greater perceived effort during conversation while driving (Tractinsky et al. 2013). Even under single-task driving conditions, older adults tend to leave more headway between themselves and a leading car to adapt to challenging road conditions, but this compensatory strategy use is associated with greater self-reported workload (Andrews and Westerman 2012).

In sum, the more ecological studies of cognitive multitasking reveal age-related declines in performance, similar to the more classical experimental paradigms. The ecological multitasking studies also raise the issue of voluntary avoidance or cessation of divided attention situations, as in distracted driving, or the de-emphasis of one component task in synthetic workload situations. At first glance, this voluntary shift in task emphasis might be considered a failure to adhere to the instructions to treat each task with equal importance; however, the research on variable priority training of dual-task performance suggests that older adults can learn to allocate their attention with varying degrees of emphasis with practice (Kramer et al. 1995). In more ecological test situations, participants are typically instructed to apply equal emphasis to each task, such as driving while conversing, or walking while listening, for example. However, it would seem judicious and adaptive to prioritize safety in such circumstances (Li et al. 2005). Observations of age-related shifts in multitasking strategy appear even in the highly controlled PRP paradigm (e.g., Glass et al. 2000), in studies of dual-task training, and neuroplasticity (Erickson et al. 2007), suggesting that age-related differences in divided attention performance may be due to age-related declines in putative cognitive processes, such as coordination processes and working memory capacity, as well as differences in motivational factors, such as perceived task difficulty or personal safety.

1.4 Cognitive Multitasking: Conclusions and Considerations

Together, the literature on aging and cognitive multitasking, including switching, dual-tasking, and more ecological multitasking scenarios, converge in demonstrating substantial age-related declines in coordinating two relevant task sets, as in the case of global switching costs and in the case of simultaneously performing more than one cognitive task. As suggested in Verhaeghen's (2011) meta-analytic findings, both global task switching and dual-task coordination show age-specific deficits independent of the effects of general slowing or performance on the component tasks themselves.

The research on complex multitasking and aging has rapidly expanded with the development of compelling immersive displays (e.g., Wechsler et al. 2018) and rich, dynamic multi-sensory environments. Such real-world multisensory simulations have enabled the closer consideration of how basic multitasking processes interact with other aging systems, such as visual, auditory, and sensorimotor declines (Campos et al. 2018; Li and Lindenberger 2002; Neider et al. 2011). The next major section considers sensorimotor-related multitasking, based primarily in the movement sciences (Rehabilitation, Kinesiology, Biomedical Engineering) and borrowing heavily from the basic cognitive literature on dual-task performance. Given that the majority of chapters in this volume focus on cognitive multitasking, we have opted to provide more background on common methods for the assessment of motor performance in the next section, drawing parallels with studies of cognitive multitasking methods and findings where applicable.

2 Cognitive–Motor Dual-Tasking and Aging

The issues of resource competition and interference in older adults, which have been explored in cognitive task switching and divided attention experiments, parallel the issues examined in the cognitive–motor dual-task literature. This work was instigated in a seminal study by Lundin-Olsson et al. (1997) who demonstrated the attentional demands of walking, as well as the clinical implications of poor cognitive–motor dual-tasking abilities. Specifically, the authors reported that in older nursing home residents, the inability to sustain a conversation while walking predicted future risk of falling. This early recognition of the cognitive and cortical involvement in gross motor control led movement scientists to incorporate dual-task designs in the analysis of gait and posture. This zeitgeist was acknowledged in Woollacott and Shumway-Cook's (2002) systematic review of studies concerning the role of attention in the control of posture and gait. Nearly two decades later, researchers are continuing to explore the interaction between cognition and mobility in old age in order to better understand resource competition and its impact on motor functioning.

In the cognitive–motor dual-task design, a cognitive task is completed concurrently with a motor task – most commonly walking or standing balance. Several techniques using this approach have been borrowed from the cognitive multitasking literature, but most prominently, performance during the single-task condition (e.g., standing or walking without the cognitive task) is compared to the dual-task condition. If performance decreases when completing the cognitive and motor task simultaneously, compared to when the tasks are completed separately, it suggests that they rely on common cognitive resources to support them.

Researchers have been interested in examining dual-task costs across different facets of motor behavior in order to elucidate the nature of interference. The most frequently reported characteristic of gait is walking speed (i.e., the time it takes to walk a certain distance; Gomes et al. 2016). Postural control, which can be defined as the control of one's body position in space in order to maintain balance, also encompasses gait and other locomotor activities (e.g., chair rising, gait initiation, steady-state walking). However, balance is more commonly assessed in a static (i.e., standing without movement) or dynamic position (i.e., alignment of one's body in response to movement such as a platform perturbation) where the amount of body sway is recorded. While the cognitive multitasking literature typically necessitates the measurement of performance across both the primary and secondary cognitive tasks, it is more common to measure just the motor performance in the cognitive–motor dual-task literature. However, in recent years, there has been movement toward measuring performance in both the motor and cognitive domains and comparing the relative performances across each task in order to accurately interpret dual-task interference and priority (Li et al. 2005; Plummer and Eskes 2015). This approach allows for the examination of the attentional strategy used, as well as potential trade-offs between tasks. There are a multitude of cognitive tests that have been used in the context of cognitive–motor dual-task research, of which the most common include working memory tasks (e.g., n-back, random number generation), executive function tasks (e.g., Stroop, verbal fluency), and arithmetic tasks (e.g., serial subtraction, counting). The most commonly reported outcome measure is cognitive accuracy (i.e., number or percent correct); however, reaction times and the number of errors are also commonly reported.

2.1 Dual-Task Gait and Aging

In regard to the dual-task gait literature, gait speed is most commonly examined. However, other aspects of gait that are often measured in the context of dual-tasking include stride length (i.e., average distance between footfalls), stride time (i.e., average time between footfalls), and stride variability (i.e., magnitude of stride-to-stride fluctuations in time or length). Gait speed can be measured by stopwatch, whereas more complex spatial and temporal gait parameters are typically measured by instrumented walkways with embedded pressure sensors. Foot switches are also used to measure the temporal characteristics of gait, such as stride time, when participants are required to walk on a treadmill at a pre-determined pace. When examining the degree of dual-task interference, researchers typically characterize these gait parameters as an average over multiple gait cycles (i.e., the cycle between a heel strike of one foot and the heel strike of the same heel in preparation for the next step). However, drawing on the cognitive dual-task methods of Posner and Boies (1971), which enable one to examine the differential impact of the processing stage (i.e., input, processing, response), some motor dual-task researchers have divided the gait cycle into phases (e.g., swing/no-contact, stance/contact) in order to identify when a processing bottleneck occurs (e.g., Fino et al. 2018; Shimizu et al. 2018). For instance, the gait cycle can be divided into phases of double-support (i.e., both feet in contact with ground), heel contact with weight transfer, toe-off in early swing, or single-support in mid-swing. The degree of dual-task interference can then be compared across gait phases to infer which aspects of the gait cycle require cognitive resources (e.g., single-support, when stability is reduced). Taken together, there are a number of methods for measuring the different characteristics of gait, all of which can be used to better understand resource competition and age-related differences in dual-task performance.

In healthy participants, cognitive–motor dual-tasking typically causes a reduction in gait speed, a decrease in stride length, and an increase in stride time variability (Al-Yahya et al. 2011). These dual-task costs to gait performance are more pronounced in healthy older adults (Smith et al. 2016) and even more so in clinical populations such as MCI and AD disease (Muir et al. 2012). Hearing loss can also negatively impact dual-task walking performance, with greater dual-task costs being observed in gait speed and cadence in older adults with increasing severity of hearing loss (Wollesen et al. 2018). Moreover, while slow walking speed (<1 m/s) has been associated with fall risk (Verghese et al. 2010) and all-time mortality (Studenski et al. 2011), the combination of walking with a cognitive task may increase sensitivity in detecting health impairments. Specifically, slower dual-task walking speed is a sensitive predictor of MCI (MacAulay et al. 2017), future incident dementia (Montero-Odasso et al. 2017), and fall risk (Wollesen et al. 2019).

A common interpretation for the decrements observed during dual-task walking is due to competition among available resources (e.g., attention, working memory, executive function). Measurement of brain activity while walking has been useful for strengthening this interpretation by providing evidence about the impact of cognitive–motor dual-tasking on neural efficiency. In recent years, there has been a proliferation in the use of functional near infra-red spectroscopy (fNIRS) to better understand the complex interaction between cognitive and motor neural circuits (Ferrari and Quaresima 2012; Udina et al. 2020). This neuroimaging approach is similar to functional magnetic resonance imaging (fMRI) but is less sensitive to motion artifact, making it ideal for experiments involving walking. Current evidence suggests that dual-task walking leads to greater activation in areas related to higher cognitive control (i.e., prefrontal cortex; PFC) than walking alone (Hamacher et al. 2015). However, there are mixed findings regarding whether this upregulation is even more pronounced in late adulthood. Specifically, some studies have shown a bilateral increase in the PFC during dual-task walking in older adults compared to younger adults (Mirelman et al. 2017; Ohsugi et al. 2013;), whereas others have shown comparable activity (Fraser et al. 2016), or even greater activity in younger adults (Holtzer et al. 2011). In clinical populations, such as stroke (Al-Yahya et al. 2016), MCI (Doi et al. 2013), and Parkinson's disease patients (a neurodegenerative disease characterized by tremor, freezing of gait, and rigidity in movement; Stuart et al. 2019), PFC activity appears to be augmented to a greater extent during dual-tasking. Taken together, there is strong evidence to suggest that PFC activity increases under greater attentional demands and may be exacerbated by age and health status, which could reflect a compensatory mechanism to neural degeneration (Udina et al. 2020).

2.2 Approaches to Dual-Task Gait Research: Impact on Interference

While the standard method used in dual-task gait research requires participants to complete a walking and a cognitive task concurrently, there are a number of adaptations that can be made, all of which may impact the level of dual-task interference observed on cognitive, motor, or neural indices. These include altering the complexity or difficulty of the concurrent task (e.g., increasing cognitive load, adding obstacles, increasing speed of walking), adapting the instructions to prioritize one task over the other, or changing the walking terrain (e.g., treadmill or overground walking).

2.3 Varying Cognitive Load

One methodological adaptation that has been shown to impact dual-task gait performance is increasing the level of cognitive load. Common tasks that can be used to increase cognitive load include the auditory *n*-back task (McMillan et al. 2007) or the serial subtraction task. In the *n*-back task, participants hear a series of numbers and are asked to recall the number they heard *n* digits earlier. In the least cognitively demanding condition, participants need to repeat the number they last heard (i.e., 0-back). Working memory demands increase when the participant needs to recall a number that is a greater distance away from the number they are currently hearing (e.g., 3-back). In the serial subtraction task, participants are given a number and are asked to continually subtract a certain amount from that number. The cognitive load is based upon the subtraction number (i.e., subtractions of one or three are considered a small cognitive load, whereas subtractions of seven are a higher cognitive load).

The level of cognitive load may also be titrated across participants ahead of testing in order to better understand the nature of dual-task interference. This titration method was borrowed from the divided attention literature (e.g., Baddeley et al. 1986), wherein the level of task difficulty is individually adjusted for each participant to ensure that performance meets a certain accuracy threshold (e.g., 60%). While this approach has been used less frequently in the cognitive–motor dual-task literature, a few studies have done this by equating memory performance in younger and older adults (i.e., training across several sessions to memorize a list of words until participants reach a pre-specified criterion level) before the addition of a secondary walking task (e.g., Li et al. 2001; Lindenberger et al. 2000). Use of this method can enhance the interpretability of the observed age differences in dual-task interference to gait. Specifically, if the level of cognitive difficulty is equated across younger and older adults, slower gait speed during dual-tasking is likely due to reduced attentional resources in older adults.

The impact of increasing cognitive load on step or stride variability has been shown to follow a U-shaped function, particularly in older adults (Decker et al. 2016; Lövdén et al. 2008). More specifically, when there is no concurrent cognitive task, attention can be exclusively directed toward walking. Given that attention is not typically directed entirely to our walking patterns, this can be unnatural and actually limit performance (i.e., increased stride variability). When a cognitive task is introduced, but the demand remains low (e.g., 1-back), it is thought to promote an *external* focus of attention that allows the motor system to self-organize and execute movement appropriately, without having to focus on movement *per se* (Lövdén et al. 2008). However, as cognitive demands increase (e.g., 2-back), the focus of attention is thought to shift *inward*. Movement then becomes the target of top-down cognitive control, which interferes with the inherent organization of the motor system and diminishes motor performance. Moreover, as cognitive difficulty increases, there is greater competition for attentional resources, which can further reduce motor performance in older adults with lower cognitive capacity. Taken together, the U-shaped function observed with increasing cognitive load may be caused by a trade-off between an external focus of attention and competition for attentional resources in late adulthood.

In regard to the impact on cognitive task performance, researchers have also demonstrated that performance on the cognitive task while walking is differentially impacted by age and the level of cognitive task difficulty. Specifically, Srygley et al. (2009) found that in younger adults, concurrent walking only reduced accuracy of serial 7 subtractions, but not serial 3 subtractions. In contrast, in older adults, performance was reduced in both the serial 3 and 7 subtraction tasks while walking, which appeared to be driven by age-related declines in executive functioning. As such, walking appears to have a detrimental effect on cognitive performance in both healthy young and older adults, but only when the cognitive task difficulty exceeds the individual's executive function capacity.

In a study by Nieborowska et al. (2018), the effect of age and cognitive load on dual-task walking and listening performance (i.e., identifying target words among competing sentences) was examined in a virtual street crossing design (see also Neider et al. 2011). Specifically, the level of cognitive load was adapted by presenting the target sentence in a location that had either lower (higher cognitive load) or greater probabilistic certainty (lower cognitive load). Results demonstrated that older and younger adults had similar dual-task costs in their word recognition accuracy when the location of the target sentence was uncertain, perhaps indicating that the level of cognitive demand surpassed the attentional resources similarly across age groups. However, older adults showed greater dual-task costs in their word recognition accuracy compared to younger adults when the location of the target sentence was certain, indicating that the less demanding cognitive condition exceeded the attentional resources of older adults, but not younger adults. Finally, dual-task costs to stride time variability were found to be lower in older adults compared to younger adults across both listening conditions, suggesting that they may prioritize their walking at the expense of their cognitive performance in order to preserve stability. A similar study was conducted in the context of age-related hearing loss, which demonstrated reduced word recognition accuracy across all listening conditions compared to older adults with normal hearing (Lau et al. 2016). This finding suggests that age-related hearing loss may make listening more cognitively demanding, which further exacerbates the effects of dual-task walking and cognitive load on cognitive performance.

Increasing cognitive load has also been found to impact dual-task performance in clinical populations. Specifically, Hunter et al. (2018) showed that in healthy older adults, dual-task costs to gait speed and cognitive accuracy were only found at high levels of cognitive load (e.g., serial 7s vs. serial 1s). However, in older adults with MCI, dual-task costs to gait speed and cognitive accuracy were found across both high and low levels of secondary cognitive task demand (Hunter et al. 2018). This finding highlights the greater vulnerability of dual-task performance for people with MCI with any additional level of cognitive demand. The level of cognitive load added during walking has also been shown to influence the sensitivity of detecting health-related outcomes. For instance, cognitive tasks that place greater demands on executive functioning are better able to discriminate between older adult fallers and non-fallers, as well as older adults with a fear of falling (Wollesen et al. 2019).

Neural activity during dual-task walking, as measured with fNIRS, also appears to be impacted by the type of secondary cognitive task. A systematic review revealed that PFC activity was most commonly increased in studies involving walking with verbal fluency or arithmetic tasks (Pelicioni et al. 2019). While this finding was consistent across both younger and older adults, clinical populations with balance disorders (e.g., stroke survivors, multiple sclerosis) tended to have greater PFC activity during dual-task walking than single-task walking irrespective of the type of secondary cognitive task (Pelicioni et al. 2019). This suggests that individuals with balance disorders may require greater attentional resources to ensure safe walking. This finding was partially replicated in a study involving sub-acute stroke patients. Specifically, Hermand et al. (2019) found that oxygenated hemoglobin was significantly increased during walking compared to standing, but there were no further augmentations in brain activity with increasing cognitive load. Notably, there was an increased cost to cognitive performance with increasing cognitive load (i.e., from 1-back to 2-back), but not to gait performance. This may suggest that in a sub-acute stroke population greater prioritization is given to the motor task to ensure stability. The similarity in brain activity with increasing cognitive load may therefore represent neural inefficiency, leading to dual-task interference in cognitive performance.

2.4 Obstacle Negotiation

Given that falls in late adulthood are most frequently caused by tripping or tripping over an object, a considerable amount of research has also been devoted to measuring dual-task interference in the context of obstacle negotiation. In this design, participants are typically asked to walk along an instrumented walkway or corridor while completing a secondary cognitive task until they reach an obstacle, which they have to step over and continue walking. Video cameras and motion-capture sensors are often used to measure the spatiotemporal aspects specific to obstacle clearance, including the distance of the trailing foot before the obstacle, the vertical foot clearance over the obstacle, the distance of the leading foot after the obstacle, and step length and foot position relative to the obstacle.

Obstacles are typically avoided by directing one’s gaze at the ground ahead, identifying the location and characteristics of the obstacle, and then adapting one's gait in order to step over the obstacle safely. While this process requires attentional resources, early research only showed age differences by altering the time course of when the obstacles appeared (i.e., older adults have greater difficulty clearing unanticipated obstacles compared to younger adults; Chen et al. 1994). However, by introducing a secondary cognitive task, Chen et al. (1996) later demonstrated that dividing attention reduces obstacle avoidance abilities in older adults more than in younger adults (i.e., older adults made more frequent foot contact with the obstacles). Since these seminal studies, other researchers have consistently demonstrated that during dual-tasking older adults have altered obstacle clearance patterns (e.g., smaller or more variable distance between foot and obstacle during clearance), increased contact with the obstacle, as well as reduced gait speed when approaching the obstacle (Harley et al. 2009; Hegeman et al. 2012; Schrodt et al. 2004). Moreover, cognitive performance is also found to decrease when negotiating obstacles in older adults (Schrodt et al. 2004), highlighting the greater attentional demands required to walk over obstacles among the already limited resources in older adults.

Given that tripping over obstacles can impose significant health problems and increase disability, understanding the involvement of attentional resources required during obstacle negotiation in both healthy aging and clinical populations is paramount to improving health-related quality of life. In comparing older adults with a history of falls, Yamada et al. (2011) found that under dual-task walking conditions, fallers chose to transfer their gaze toward the obstacle at a significantly earlier time than non-fallers. This was in contrast to single-task walking, where both fallers and non-fallers directed their gaze toward the obstacle at an equal number of steps before. Therefore, older adults with a history of falls appear to implement an adaptive strategy to reduce the risk of falling as attentional demands increase. In another study of older adults with a history of falls, dual-tasking with obstacle negotiation was associated with reduced gait speed, increased stride time, and increased toe clearance from the obstacles compared to older adults without a history of falls (Siu et al. 2008). Again, this suggests that older adults with balance impairments learn to use an appropriate strategy under high attentional demands in order to reduce the risk of future falls.

Dual-task obstacle negotiation has also been studied in stroke survivors with and without hemi-lateral neglect (Aravind and Lamontagne 2017). This is a common attentional-perceptual disorder that is found following stroke, which reduces the person's ability to orient and respond to stimuli on the side opposite of the brain lesion. Researchers have found that under dual-task conditions, stroke survivors with hemi-lateral neglect more frequently collide with obstacles, have shorter distances to clearing the obstacle, make more cognitive errors, and have greater locomotor dual-task costs, especially as cognitive demands increase (i.e., increased inhibitory control; Aravind and Lamontagne 2017). These findings suggest that the planning and execution of adaptive strategies to avoid obstacles in stroke patients with hemi-lateral neglect are impaired, leading to greater dual-task interference effects.

Taken together, it is evident that obstacle negotiation during dual-task walking is deteriorated across certain pathophysiological conditions, particularly when there is damage to perceptual or attentional abilities. However, dual-task walking with obstacle negotiation appears to be preserved or adapted in older adults with balance impairments. This is an important area for further research, particularly in the rehabilitation setting, to teach older adults with physiological or cognitive impairments how to adapt their gait in order to avoid future falls and disability.

2.5 Speed of Walking

In everyday life, walking at a faster pace may be required – for instance, when late for an appointment or when needing to catch a bus. As such, another common modification made to the dual-task walking paradigm is instructing participants to walk at a different gait speed (e.g., slow, normal, or fast). Participants can be instructed to do this by following their own perception of what they consider to be slow, usual, or fast, or, alternatively, they can be instructed to follow the speed of a metronome with tempos presented at varying beats per minute. In the latter technique, the metronome can be adjusted to the participants' typical cadence, such that the beats can be presented at a certain percentage slower or faster than their usual walking speed.

In the aging literature, there is evidence that dual-task costs to gait speed during fast-paced walking are greater in older adults than in younger adults (Krampe et al. 2011). Additionally, performance on tests of executive function (i.e., Trails Making Test B/A) has been found to correlate with dual-task walking speed, number of steps, and stride duration under fast-paced walking conditions in older adults (Hobert et al. 2017). Specifically, older adults who have poorer executive function walk more slowly, take less frequent steps, and have shorter stride durations when instructed to walk at a fast pace while completing a simultaneous cognitive task. This relationship between executive functioning and dual-task walking is weaker when older adults are instructed to walk at their usual walking speed. Therefore, walking at a fast pace may increase attentional demands, which could further exacerbate dual-task interference in older adults with lower cognitive resources.

Tests of fast walking may also better predict age- and health-related declines in functioning than walking at usual speed. For instance, in a longitudinal study where changes in memory, executive function, and gait speed were assessed over time, researchers found that declines in fast-paced endurance walking preceded declines in executive function and memory (Tian et al. 2017). Greater stride time variability during fast-paced walking has also been associated with the status of MCI (Beauchet et al. 2013). Additionally, slower fast-paced walking speed has been found to better predict future falls compared to usual walking speed (Rosso et al. 2019). These findings highlight the sensitivity of fast-paced walking in detecting future cognitive decline and fall risk. However, further research is needed to determine whether sensitivity in detecting future cognitive impairment and fall risk is enhanced to an even greater extent when fast-paced walking is combined with a concurrent cognitive task.

In regard to neural activity, researchers have compared the effect of dual-task walking under usual or fast-paced walking conditions in healthy older adults and older adults with chronic obstructive pulmonary disease (COPD) using fNIRS (Reid et al. 2019). Patients with COPD have long-term breathing problems, which make everyday activities such as walking more challenging and fatiguing. Cognitive impairment is also common in patients with COPD due to hypoxemic-induced neural damage. Reid et al. (2019) found a greater increase in oxygenated hemoglobin levels in the left dorsolateral PFC in patients with COPD compared to healthy older adults during both usual and fast-paced walking. However, when comparing oxygenated hemoglobin levels between single- and dual-task walking (e.g., spelling backward) at a usual or fast pace, PFC activity only significantly increased in healthy older adults but not in patients with COPD. Notably, both walking speed and cognitive performance significantly decreased under fast-paced dual-task conditions. These findings are similar to what was seen in balance-impaired older adults with increasing cognitive load, where there was little additional increase in brain activity compared to walking alone. This could suggest that older adults with COPD have a limited amount of neural and attentional resources, which may reach its capacity under simple walking conditions. This is unlike healthy younger and older adults who appear to have more resources that they can utilize as the cognitive and physical demands increase. Further research on the effects of fast-paced dual-task walking on behavioral and neural processes in more diverse health conditions is warranted.

2.6 Task Prioritization

A substantial amount of research has also been dedicated to examining the prioritization of either the motor (i.e., “posture-first” strategy) or cognitive (i.e., “posture second” strategy) task during dual-tasking. This concept was first introduced by Shumway-Cook et al. (1997) and is well-demonstrated in a study by Li et al. (2001), who showed that older adults spontaneously prioritized walking to the detriment of secondary cognitive task performance, perhaps to increase safety and reduce the risk of falls. Notably, in this study, the difficulty of the cognitive and motor tasks was titrated (i.e., participants were trained to reach asymptotic performance levels for the walking and memory tasks). Therefore, it is unlikely that the smaller dual-task effect observed in the walking domain was due to the fact that walking is a more habitual activity compared to memorizing.

The effect of prioritization on dual-task performance has also been examined by altering task instructions so that participants either prioritize both tasks equally or prioritize the walking or cognitive task over the other. In a study comparing the effect of prioritization instructions on dual-task performance in healthy older adults, Verghese et al. (2007) found reductions in gait velocity and cadence when participants were asked to pay more attention to the cognitive task (reciting alternating letters of the alphabet) compared to paying equal attention across tasks. In contrast, cognitive accuracy was improved under the same task emphasis conditions. Therefore, it appears that older adults have a speed-accuracy trade-off when instructed to prioritize the cognitive task, whereby they may compensate by slowing their walking speed in order to avoid instability.

This is consistent with other research by Yogev-Seligmann et al. (2010) who showed that older adults had reduced gait speed when they were instructed to either emphasize cognitive performance (verbal fluency) or were given no prioritization instructions compared to when they were instructed to emphasize walking. Given that walking speed was similar when older adults were not given any prioritization instructions or were instructed to prioritize cognitive performance, it appears as if older adults inherently prioritized their cognitive performance, which is contrary to the well-established postural prioritization hypothesis. This finding could suggest that older adults imposed a compensatory attentional allocation strategy that is dependent on task demands and experimental instructions. As older adults were able to prioritize walking performance when instructed to do so, this finding further highlights the flexible nature of attention in older age. This is consistent with earlier research by Kramer et al. (1995), who demonstrated improvements in cognitive dual-task performance (i.e., a scheduling and working memory task) following variable priority dual-task training (i.e., participants needed to vary their priorities between the two tasks).

Task prioritization has also been found to change as a result of increased cognitive load. Specifically, in a study by Li et al. (2012), older adults were found to maintain their cognitive performance during dual-task walking at varying levels of cognitive difficulty (i.e., serial 1 or 7 subtractions), but adaptively increased their stride time and stride length. As such, older adults were able to flexibly adapt their prioritization strategy to the cognitive domain while modifying their gait to ensure safe walking.

Finally, this compensatory attentional allocation strategy has been demonstrated in studies of increasing cognitive demands and task prioritization instructions. Specifically, Maclean et al. (2017) demonstrated that when cognitive load is low (i.e., serial 3 subtraction), older adults have greater cognitive dual-task benefits (i.e., are more accurate when completing both tasks simultaneously) when asked to prioritize cognitive performance compared to gait. However, when the cognitive load is increased (i.e., serial 7 subtraction), task instructions do not appear to impact cognitive performance (i.e., older adults had similar cognitive performance when asked to prioritize cognition or gait). This finding may suggest that older adults prioritize their gait when the cognitive task demands greater attentional resources, regardless of instructions, in order to secure gait stability.

While healthy older adults tend to appropriately prioritize their gait to the detriment of cognitive performance during dual-tasking to ensure stability and reduce the risk of falls, older adults with certain health conditions, such as Parkinson's disease (PD), have been observed to use a "posture second" strategy (Bloem et al. 2006). Specifically, in a systematic review conducted by Bloem et al. (2006), the researchers found that older adults with PD froze more frequently and made more cognitive errors, particularly when the tasks became more demanding. The authors speculated that some patients with PD are "unable to properly judge the risk of their actions," particularly if they have poor insight into the severity of their mobility deficits (Bloem et al. 2006, p. 202). As such, PD patients may unintentionally exacerbate their risk of falling, while in dual-task situations, by not prioritizing their gait.

Although PD patients may implement maladaptive prioritization strategies, researchers have shown that attentional allocation during dual-tasking is flexible in older adults with PD. Specifically, Kelly et al. (2012) showed that altering instructions to prioritize walking performance led to increased gait velocity, larger stride length, and higher cadence, while maintaining gait stability. This appeared to come at a cost to cognitive performance, as greater dual-task costs were observed in cognitive accuracy and reaction times when instructed to prioritize walking. These findings were comparable with younger adults, which suggests that postural prioritization in PD is a dynamic process that can be modified by instructions and may be a viable rehabilitation approach to improve dual-task walking in this population.

The effect of task prioritization has also been examined in older adults with cognitive impairment. Specifically, Lee and Park (2018) found that dual-task costs to gait velocity and stride time variability were significantly increased in patients with MCI when instructed to prioritize either the cognitive (subtracting by 1) or walking task, compared to when no prioritization instructions were given. Compared to healthy older adults, the dual-task cost to gait velocity was almost two times greater in MCI patients when no priority instructions were given, and it was almost 3 times greater when instructions were given to prioritize either the cognitive or walking task. A similar, yet more pronounced effect was found for dual-task costs to gait variability. Interestingly, while stride time variability was highest when healthy older adults were instructed to prioritize their cognitive performance compared to walking or when given no instructions, there was no significant difference in stride time variability between either set of prioritization instructions in patients with MCI. These findings suggest that both healthy older adults and MCI patients have difficulty maintaining a "posture first" strategy when instructed to prioritize the cognitive task, with this being exacerbated in MCI patients. Moreover, instructions to emphasize walking may create a greater cognitive load in MCI patients, which can interfere with the automaticity of walking, leading to greater gait variability and reduced velocity.

2.7 Overground Versus Treadmill Walking

Multitasking in everyday life can occur on many different kinds of surfaces (e.g., on hard surfaces like while walking down the street or inside of a building or one's home, on uneven walking terrain like when hiking, or on inclines up or down a hill). However, in the laboratory, dual-task walking is typically measured on flat, hard surfaces; either on the floor, called "overground walking," or on a treadmill. In contrast to overground walking, in which both the temporal and spatial characteristics of gait can be measured, treadmill walking is typically completed at a pre-determined walking speed, which limits the ability to measure spatial gait characteristics. Additionally, overground walking can include turns, whereas treadmill walking is typically done in a continuously straight path.

While researchers initially assumed that dual-task effects would be similar across overground and treadmill walking conditions, more recent research has demonstrated important differences between these modalities. Specifically, in healthy young adults, stride time variability typically increases from single- to dual-task conditions during overground walking, whereas it has been shown to be reduced or is unchanged from single- to dual-task conditions during treadmill walking (Lövdén et al. 2008; Schaefer et al. 2010; Wrightson et al. 2016; Wrightson and Smeeton 2017). This discrepancy may be explained by the differing levels of attentional demand required during treadmill versus overground walking. Specifically, during dual-task treadmill walking, healthy older adults tend to have better cognitive performance, with relatively little cost to their gait; however, during dual-task overground walking, both cognitive and gait performance have been shown to worsen (Penati et al. 2020; Wrightson et al. 2020). As such, dual-task treadmill walking in the laboratory may not fully capture the level of cognitive control required during everyday overground walking and should be marked as an important methodological limitation.

A similar finding is evident in the aging literature. Specifically, in comparing treadmill and overground walking in healthy older adults, Simoni et al. (2013) found that dual-tasking significantly reduced gait speed, cadence, step length, stride length, and cognitive performance during overground walking, whereas there was only a dual-task effect on cadence during treadmill walking. Therefore, even in older adults who have a reduced cognitive capacity compared to younger adults, it appears that treadmill walking does not demand enough attentional resources in order to observe significant dual-task interference effects. This finding is consistent with the results of a study where multiple physical and cognitive demands of a dual-task design were manipulated (e.g., obstacle negotiation, overground vs. treadmill walking, visual vs. nonvisual secondary cognitive task; Bock 2008). Specifically, Bock (2008) found that the use of a treadmill was not essential for the emergence of age-related dual-task deficits but was rather dependent on the combination of tasks involving obstacle negotiation and greater visual demands of the secondary cognitive task. Taken together, as dual-task treadmill walking may require less cognitive control, it could underestimate the difficulties older adults encounter with multitask walking in everyday life. Further research is needed to determine whether treadmill and overground walking differ in clinical populations such as in MCI and AD.

2.8 Dual-Task Gait Research: Conclusions and Considerations

Taken together, it is clear that the dual-task walking paradigm can be very useful in characterizing normative and pathophysiological aging, particularly by increasing the sensitivity of detecting health conditions like MCI, dementia, and fall risk (Muir et al. 2012; Montero-Odasso et al. 2012). While the level of dual-task interference can be manipulated by varying the attentional demands of the cognitive or walking task, it is evident that the more challenging the task is (e.g., higher cognitive load, obstacle negotiation, fast-paced walking, overground walking), the greater the dual-task effects will be. Moreover, dual-task interference tends to be exacerbated in individuals with lower cognitive capacity, whether it be due to normative aging or a clinical health condition (e.g., MCI). In terms of task prioritization, older adults with and without a history of falls tend to prioritize gait performance at the cost to their cognitive performance in order to increase stability. While older adults with PD atypically allocate attention to the cognitive domain (i.e., have greater dual-task interference in gait performance), they can learn to adapt their attentional strategy when given instructions to prioritize gait. Finally, there is inconsistent evidence regarding neural activity during dual-task walking. However, it appears that dual-task walking causes a heightened upregulation of brain activity, particularly in the PFC, that could act as a compensatory mechanism for declining brain structure and function in late adulthood. Given the clinical implications of poor dual-task walking, it proves to be an important target for treatment. There is evidence that cognitive (i.e., executive function training), physical (e.g., aerobic exercise), or combined dual-task training improves dual-task gait in healthy older adults (e.g., see Plummer et al. 2016 and Marusic et al. 2018 for reviews). Indeed, from a neural overlap perspective, if there is a functional overlap between the trained task and the outcome measure, there is greater potential for transfer to occur (Lustig et al. 2009).

Nevertheless, there are a few methodological limitations of the dual-task gait design that should be considered for future researchers in this field. Specifically, cognitive task titration (i.e., individually equating task difficulty) is needed to accurately interpret the degree of dual-task interference to gait performance, yet it is not frequently implemented in these experimental designs. Moreover, cognitive–motor dual-task experiments tend to have poorer temporal resolution than in the cognitive multitasking literature (e.g., PRP designs). There is a subset of dual-task gait and aging studies that consider cognitive interference in the different phases of the gait cycle, but as this approach is less common, future research implementing this design is warranted. Finally, it is pertinent to consider whether deficits observed during dual-task walking in the laboratory are consistent with walking in the real world. In a study by Hillel et al. (2019), gait characteristics were measured under single- and dual-task conditions in the lab and were correlated with gait characteristics measured during daily living. The authors found that while dual-task walking in the lab correlated better with everyday walking more than single-task walking, the gait deficits were greater in the real world. This may mean that dual-task walking performance in the lab is an overestimation of walking performance in everyday situations. While the assessment of dual-task walking in laboratory settings is insightful and clinically relevant, further research is needed to evaluate whether these daily living measures of gait are sensitive in predicting adverse health events, such as fall risk, mobility impairment, and cognitive decline.

2.9 Postural Dual-Task Research

The most common measures of postural control include static balance, which refers to standing without movement (e.g., single- or double-support standing), and dynamic balance, which refers to the alignment of one's body in response to movement (e.g., perturbation of a platform). Balance can be quantified by using motion capture systems and force plates to measure the change in kinematic and kinetic variables over time, such as the center of mass (CoM) and center of foot pressure (CoP) distance. CoM is defined as the point at which the body's mass is equally balanced and is commonly used in reference to the base of support, which is the total area beneath the person they are in contact with. As such, instability increases when the CoM moves beyond the base of support, which can be due to a decrease in the base of support or an increase in the CoM. CoP refers to the point at which the pressure of the body over both feet is concentrated in one spot. Deviations in the location of CoP, as measured by the area or range of excursion, as well as the velocity of the CoP excursions, is used to quantify body sway. Researchers can also measure more qualitative aspects of balance, including the type of strategy used to recover from a perturbation, such as feet-in-place or compensatory stepping, as well as the time it takes to stabilize following a perturbation. Muscle activity, in terms of the amplitude or the latency of response following a perturbation, can also be measured during postural dual-tasking using electromyography (EMG). The muscles that are most commonly recorded include the tibialis anterior, gastrocnemius, rectus femoris, and hamstrings. Finally, cortical activity can be measured during postural dual-tasking using electroencephalography (EEG) or fNIRS (Holtzer et al. 2014).

Studies of postural dual-tasking have demonstrated significant attentional demands associated with balancing. For instance, during static balance tasks, the addition of a cognitive load has been shown to increase the area and velocity of CoP excursions, which represents increased body sway (Woollacott and Shumway-Cook 2002; Quant et al. 2004). Moreover, while a step is only required when the CoM exceeds the limits of the base of support following a perturbation, the addition of a cognitive task leads to stepping when the CoM is located in a more central location within the base of support (Woollacott and Shumway-Cook 2002). This suggests that when attentional resources are allocated to a cognitive task, compensatory stepping following a perturbation is more likely to occur even at low levels of postural threat. In healthy young adults, the simultaneous completion of cognitive and balance tasks has also been shown to decrease the amplitude of the EMG response in the lower leg muscles (Rankin et al. 2000). Reduced muscle activity during dual-tasking may suggest that less attentional resources are available to support postural control.

Similar to the dual-task gait literature, changes in brain activity in the frontal cortex have been observed during postural dual-tasking. Specifically, using EEG in healthy young adults, a platform perturbation with a simultaneous cognitive load has been shown to cause a decrease in the magnitude of the N100 response, a marker of early attentional orientation (Little and Woollacott 2015; Quant et al. 2004). Using fNIRS, postural dual-tasking (i.e., standing on one or both feet while completing a Stroop task) has resulted in an increase in oxygenated hemoglobin levels in the right dorsolateral prefrontal cortex and supplementary motor area, particularly in young adults with a high working memory span compared to young adults with a low working memory span (Fujita et al. 2016). Given that participants with better working memory had limited dual-task decrements, the increased activation may indicate that they had greater neural resources that were being recruited, which allowed for the successful allocation of attentional resources to both postural stability and executive functioning. Together, these findings support the complex nature of postural control, which requires detecting changes in kinematic variables, integrating sensorimotor information in the central nervous system, and executing the appropriate musculoskeletal response – all of which compete for attentional resources.

The attentional demands associated with postural dual-tasking are exacerbated in older adults and in populations with sensory (e.g., age-related hearing loss), cognitive (e.g., AD), or motor (e.g., PD) impairments. Specifically, older adults exhibit greater dual-task costs than younger adults both in terms of their postural performance (e.g., greater CoP areas) during static and dynamic balance tasks, as well as their cognitive performance during dynamic balance tasks (Boisgontier et al. 2013; Woollacott and Shumway-Cook 2002). This has important health implications, as increased postural sway is associated with an increased risk of falling in older adults (Melzer et al. 2004). Indeed, balance-impaired older adults with a history of falls have greater CoP velocities and take longer to stabilize their CoP following a perturbation when there is a concurrent cognitive task, compared to healthy older adults (Brauer et al. 2001). Healthy older adults also have stronger muscle contractions in the lower leg (i.e., tibialis anterior) during static dual-task balancing compared to younger adults, which may act to compensate for declining attentional resources and help stabilize the ankle joint (Makizako et al. 2013; Melzer et al. 2001). Moreover, following a perturbation, older adults are more likely to initiate a stepping strategy, whereas younger adults are more likely to use an ankle flexion strategy (Brown et al. 1999). Dual-task deficits appear to be even more pronounced in patients with AD or PD, with particular deficits observed in the cognitive domain at low levels of postural demand (de Andrade et al. 2014; Manckoundia et al. 2006; Rapp et al. 2006). This may suggest that older adults with cognitive or motor impairments prioritize postural stability when engaged in a situation requiring simultaneous completion of a balance and cognitive task.

Finally, there is inconsistent evidence regarding the effect of postural dual-tasking on brain activity across younger and older adults, with some researchers reporting greater brain activity in prefrontal and temporal regions in older adults (Rosso et al. 2017) and others showing no differences across younger and older adults (Marusic et al. 2019). Importantly, while Rosso et al. (2017) found dual-task performance (i.e., both cognitive accuracy and postural sway) to be similar across younger and older adults, Marusic et al. (2019) found that cognitive and postural performances were worse in older adults during both single- and dual-task conditions compared to younger adults. As such, the observed increase in cortical activation in older adults by Rosso et al. (2017) may represent a compensatory mechanism to help maintain postural stability in the face of declining brain structure with age. However, future research is needed to elucidate these inconsistencies. There is also limited research on the effect of postural dual-tasking on neural activity in age-related health conditions, so future research is warranted.

3 Approaches to Postural Dual-Task Research: Impact on Interference

Much like the dual-task gait research, there are a number of modifications that can be made to the standard postural dual-task experiment, all of which can impact the level of dual-task interference observed. Such alterations include the level of cognitive load, choice of cognitive modality (i.e., auditory or visual) or response type (i.e., silent or aloud), difficulty of the postural task (e.g., foot placement, single-leg vs. double-leg stance), and manipulation of sensory parameters (e.g., foam surface, eyes closed, conflicting sensory information).

3.1 Varying Cognitive Load

The impact of cognitive load on balance performance in older adults shows a similar U-shaped function to that seen in the gait literature. Specifically, while a simple cognitive task (e.g., choice reaction time) may improve balance performance compared to balancing alone, when the cognitive task complexity increases, balance becomes impaired (Huxhold et al. 2006). One explanation for this finding is that devoting conscious control of attention over a highly automated task such as balancing is unnatural and detracts from efficient motor coordination. Indeed, there is evidence that an external focus of attention (e.g., movement effects on the environment, a distal cue) compared to an internal focus of attention (e.g., on one's posture) is more beneficial to postural performance (Chiviacowsky et al. 2010). Therefore, a simple cognitive task may cause distraction from postural sway, leading to a greater external focus of attention and facilitating balance. However, at higher levels of cognitive interference, resource competition becomes detrimental to motor performance (e.g., increased COP area and sway; Fraizer and Mitra 2008; Huxhold et al. 2006).

The threshold for this switch-point (i.e., the point at which the cognitive task moves from being facilitative to being detrimental to balance performance) is lower in older adults than in younger adults. Specifically, Huxhold et al. (2006) demonstrated that in older adults, compared to single-task standing, the addition of a simple cognitive task (i.e., choice reaction time, watching digits on a screen) led to reduced COP areas, whereas more cognitively complex tasks (i.e., digit/spatial 2-back) increased COP areas. In contrast, younger adults showed improved COP areas with the addition of any cognitive task, even at the highest level of complexity. This finding may suggest that the younger adults had ample cognitive resources to allocate to the postural task, even in the most cognitively complex condition, which led to the facilitation of balance performance due to an external focus of attention. However, in older adults, reduced cognitive capacity would lead to competition among resources during the cognitively demanding working memory tasks, thereby leading to detrimental postural performance.

Equating the cognitive task difficulty using the titration technique described earlier (e.g., Baddeley et al. 1986) has also been examined in a postural dual-task design. Specifically, Doumas et al. (2009) trained younger and older adults to perform an n-back task while increasing the level of task difficulty (i.e., from 2-back to 3-back with increasingly faster presentation rates). Participants were trained on the cognitive task until they achieved 80–100% accuracy under single-task conditions in order to establish equal performances across participants and aid in the interpretation of age differences. Results revealed differences in task prioritization with increasing cognitive load. Specifically, when the cognitive load was increased, older adults showed greater dual-task costs in both their posture and cognition, whereas younger adults only had greater dual-task costs in their working memory performance. However, over repeated practice sessions, older adults showed greater improvements in posture (i.e., reduced sway), whereas younger adults showed greater improvements in working memory performance. These findings suggest that older adults may prioritize their stability under more cognitively demanding dual-task conditions due to limited resources.

Finally, it could be speculated that with increasing cognitive load, older adults with cognitive or motor impairments may prioritize the postural task to an even greater degree or that the cognitive threshold for the switch-point in the U-shaped function on postural performance would be even lower than that of healthy older adults. However, there is a lack of research investigating the effect of cognitive load on dual-task balance performance in this population, and therefore future research is warranted.

3.2 Cognitive Task Modality/Response Format

The cognitive task modality (e.g., visual or auditory), as well as the response format, also appear to impact the level of dual-task interference observed. In order to examine the effect of cognitive task modality on dual-task performance, Kerr et al. (1985) had young adults hold a tandem balance position (i.e., heel/toe stance) while blindfolded and concurrently completing either a spatial memory task or a nonspatial memory task. The authors found that memory performance was worse while balancing, but only for the spatial memory task, suggesting that cognitive spatial processing may overlap with the resources needed to maintain balance (see also Maylor et al. 2001; Maylor and Wing 1996). In addition to the cognitive task modality, the effect of response format on dual-task posture has also been examined. For instance, Yardley et al. (1999) asked healthy young adults to maintain their balance while completing a serial seven subtraction task, wherein responses were either made aloud or silently. The authors found that oral responses led to greater deficits in postural performance (i.e., increase sway path and frequency) compared to silent subtractions. This finding was replicated in a study by Dault et al. (2003), which investigated an array of cognitive tasks that required different levels of attention – all of which led to reduced postural performance when responses were articulated aloud rather than when made silently. Another method to investigate the effect of cognitive task modality on dual-task postural performance is by modifying the inter-stimulus interval (ISI) of either visually or verbally presented information. For instance, Polskaia and Lajoie (2016) assessed static postural control in younger adults during an auditory or visual counting task where the ISI varied between 2 and 5 seconds. The results indicated that the visual cognitive task led to better postural control (i.e., reduced sway areas and variability) than the auditory cognitive task but did not impact cognitive performance. Additionally, the continuous tasks (i.e., ISI of 2 sec.) led to more cognitive errors than the discrete tasks (i.e., ISI of 5 sec.) but had little impact on postural performance. These findings from healthy young adults suggest that an oral response format may negatively impact dual-task postural performance, whereas visual cognitive tasks may improve postural performance.

In regard to the aging literature, some inconsistent findings emerge when comparing postural dual-task performance across different cognitive task modalities. Specifically, Richer and Lajoie (2019) demonstrated that in healthy older adults, a visual counting task completed concurrently with a static balance task led to a reduction in sway area and variability compared to an auditory counting task, with no impact of task modality on cognitive performance. One explanation for this finding may be due to the congruency between the sensory requirements of the dual-task (i.e., both the postural task and cognitive task require vision). Another possible explanation offered by the authors is that the visual task acted as an anchor to help stabilize the participants. In contrast to this study, Redfern et al. (2001) found that during the concurrent completion of a simple reaction time task and a static balance task, reaction times were slower in the visual modality than in the auditory modality, with this effect being more pronounced in older than younger adults. Moreover, older adults showed increased postural sway with the addition of the reaction time task, whereas younger adults did not; yet, there was no differential effect of the task modality (i.e., the same amount of increased sway was observed in both the visual and auditory tasks for older adults). The discrepancy observed across studies may be due to the measurement of reaction times rather than cognitive accuracy, which may be more sensitive to detecting impairment. Moreover, this study involved more complex postural conditions, which may have limited the amount of possible improvement gained from visual stimuli on postural stability. There is limited research in the literature examining the effect of cognitive task modality or response type on dual-task postural performance in age-related health conditions, such as MCI. As such, future research is needed.

3.3 Physical Task Complexity

The level of dual-task interference is also impacted by the complexity of the postural task. A variety of methodologies exist to adapt postural difficulty. For static balance, such adaptations include foot placement (i.e., together, apart, tandem, semi-tandem) and leg stance (i.e., single- or double-leg stance). For dynamic balance, postural difficulty can be manipulated by altering the size or velocity of the perturbation, the direction of the perturbation, or the interval between the stimulus onset and the perturbation. Additionally, sensory manipulations can increase the complexity of the postural task by minimizing or altering the amount of sensory input needed to maintain balance. Such adaptations include altering visual input by having participants perform a postural task with their eyes open or closed or by stimulating visual motion cues (e.g., by projecting moving vertical lines). In the latter technique, reference to visual cues in one's environment is altered to induce the feeling of movement, which prompts the kinesthetic system to incorrectly adjust one's body in space to maintain balance. Somatosensory input can also be altered by changing the durability of the surface, such as standing on a hard or foam surface. Additionally, somatosensory input can be reduced by creating rotational platform movements that are in direct proportion to the participants' body sway. Using this method eliminates any source of reference to the amount of sway, which is required to successfully adjust one's posture and maintain balance.

In a study by Redfern et al. (2002), dynamic postural performance and auditory and visual reaction times were examined in a dual-task design in healthy young and older adults. The perturbations differed in terms of the size of the displacement (i.e., small vs. large), the direction (i.e., forward vs. backward), and the time interval between the cognitive stimulus and the perturbation (i.e., stimulus presented before the perturbation, at the same time, or after the perturbation). Performance on the reaction time tasks was influenced by the perturbation size before and during the perturbation, particularly in older adults. Specifically, slower responses were made in preparation of and during the large perturbations, whereas the size of the perturbation did not influence the reaction times after the onset of the perturbation. This may suggest that the preparatory and response phases of a large perturbation require greater attentional control, which shifts attention away from the cognitive task in order to prioritize postural performance. In line with this, responses to the perturbation (i.e., CoP latency) were faster in older adults than in young adults, suggesting an increased focus of attention on the postural task.

During postural dual-tasking, sensory adaptations have been shown to impact postural control (i.e., increased CoP distances) and cognitive performance (i.e., slowed reaction times) to a greater extent in healthy older adults compared to younger adults. Specifically, in a study by Teasdale et al. (1993), healthy young and older adults completed an auditory reaction time task while they were seated, standing with feet together, or standing with feet apart on either a foam or hard surface with their eyes opened or closed. The authors found that both young and older adults showed delayed reaction times as the postural task increased in complexity (i.e., sitting, standing with shoulder feet apart, standing feet together), with reaction times being greater in older adults. Reaction times were also found to increase when visual input was removed, with older adults being more impacted by the loss of vision than young adults. Finally, the reduction of somatosensory information (i.e., on a foam mat) led to an increase in reaction times for both age groups. Taken together, these results suggest that when sensory information is reduced or modified, it requires greater attentional resources to complete a secondary task, especially in older adults with reduced cognitive capacity.

Redfern et al. (2001) also examined the attentional involvement in postural control across various sensory conditions in healthy young and older adults. Participants completed different reaction time tasks, with visual/somatosensory manipulations including (1) seated, (2) standing with a stable visual environment, (3) standing with a sway-referenced floor with a fixed visual scene, and (4) standing with a sway-referenced floor and a sway-referenced visual scene. Postural sway and reaction times were greater in older adults than in younger adults, with greatest instability and slowest reactions times observed in the condition with the most conflicting sensory information (i.e., condition 4). These results suggest that as sensory information becomes unreliable, greater attentional resources are required to make sense of and integrate this information, leading to deficits in postural performance and processing speed. In older adults, poor executive functioning, particularly inhibitory control, may account for the difficulties observed in sensory integration during postural dual-tasking in order to avoid incorrect visual/somatosensory cues and readjust posture accordingly.

Finally, Doumas et al. (2008) examined the potential trade-off between postural and cognitive dual-task performance across various sensory parameters in healthy young and older adults. Participants completed an n-back working memory task while seated or while standing on a platform with no sway reference (stable), a visual sway reference (i.e., where the visual surround rotated in the sagittal plane), or a somatosensory sway reference (i.e., where the platform rotated around the ankle joint axis). In order to determine the trade-off between cognitive and postural performance during dual-tasking, the raw values were translated into proportional dual-task costs, which consider individual single-task performance in the context of dual-tasking (i.e., dual-task – single-task/single-task * 100 for both the posture and cognitive domains). The authors found an effect of age, whereby dual-task costs were greater in older adults than in younger adults. Most notably, for older adults in the sway-referenced somatosensory condition, there was a decrease in postural dual-task costs and an increase in cognitive dual-task costs. The authors also found a 40% increase in sway during the stable standing condition compared to single-task sitting. In contrast, the dual-task somatosensory sway reference led to a significant decrease in cognitive accuracy compared to single-task sitting. Given that the stable surface was the least complex condition, it suggests that older adults prioritized cognition at a cost to their postural performance (as seen by increased sway). However, in the most difficult postural condition, it appears older adults prioritized posture at a cost to their cognitive performance (as seen in the reduced cognitive accuracy). This result was not found in young adults, which suggests that older adults learn to flexibly allocate attentional resources to either prioritize cognitive performance under stable postural conditions or to prioritize postural performance when somatosensory information is compromised.

The role of sensory integration in postural-dual-tasking has also been examined in the context of older adults with balance impairments and a history of falling. In a study by Shumway-Cook et al. (1997), the effect of altering somatosensory cues on dual-task postural performance and cognitive accuracy was examined in healthy young adults and older adults with and without a history of falls using two different cognitive tasks (i.e., language processing, visual perceptual task). Results revealed an effect of somatosensory cues on postural sway (i.e., CoP displacement), but not cognitive performance. Specifically, the authors found that on a hard surface, older adults with a history of falls had greater postural sway compared to healthy young and older adults, with no difference observed between the healthy participants. In contrast, on a foam surface, postural stability differed significantly between all three groups, with the older adults with balance impairment showing the greatest amount of postural sway and the younger adults showing the most stability. These results suggest that older adults with a history of falls may have difficulty allocating attentional resources to the postural task, even in stable conditions.

In another study by Shumway-Cook and Wollacott (Shumway-Cook and Woollacott 2000), healthy young adults, as well as older adults with and without a history of imbalance, completed a postural dual-task experiment across various sensory conditions, where the cognitive task involved an auditory choice reaction time task (i.e., identifying tones as high vs. low). Visual adaptations included eyes opened, eyes closed, or visual motion (i.e., projection of a moving vertical line to simulate movement). Somatosensory adaptations included standing on a hard surface or a sway-referenced platform (i.e., surface rotated around the axis of the ankle joint in direct proportion to the participants' body sway). In regard to the cognitive results, there was no effect of age, fall history, or sensory adaptation on cognitive accuracy. However, older adults' reaction times were slower than those of younger adults. In the older adults with no history of falls, reaction times significantly increased when standing on the sway-referenced surface condition, particularly when paired with the eyes closed or visual motion conditions. While some of the older adults with a history of falls were not able to complete the most challenging conditions (i.e., sway-referenced surface), slower reaction times were observed on the hard surface when eyes were closed or when visual motion cues were given. Therefore, even on a firm surface, the attentional demands of maintaining stability in the balance-impaired older adults resulted in decreased reaction time when visual cues were manipulated. Regarding postural performance, in young adults, the addition of the choice reaction time task did not significantly affect postural sway in any of the sensory conditions. In healthy older adults, the addition of a secondary task affected postural sway only in the two most difficult sensory conditions (i.e., sway reference-eyed closed; sway reference-visual motion), when both visual and somatosensory cues for postural control were disrupted. In contrast to the young and healthy older adults, in the balance-impaired older adults, the addition of the secondary cognitive task significantly affected postural stability across all sensory conditions.

Taken together, these studies suggest that manipulating visual or somatosensory cues have little impact on cognitive accuracy during postural dual-tasking but have rather large impacts on reaction times and postural stability, particularly in older adults with a history of falls. Although this does not appear to be in line with the postural prioritization hypothesis (where greater deficits are typically observed in the cognitive domain), it may be that older adults, particularly those with a history of falls, are unable to correctly allocate attentional resources to postural performance in conditions of reduced sensory information, due to an increase in attentional demands. Of clinical relevance, this suggests that older adults with a history of falls should restrict multitasking to environments with optimal sensory conditions in order to reduce the risk of future falls.

3.4 Postural Dual-Task Research: Conclusions and Considerations

Overall, there is strong evidence for the role of attention in postural control, as demonstrated by reduced balance (e.g., increased sway area) and cognitive performance (e.g., reduced accuracy, increased reaction times) during dual-tasking. The attentional requirements of balance have been researched using a number of different experimental adaptations. For instance, increasing cognitive load has been found to follow a similar U-shaped pattern to that observed in the dual-task gait literature, wherein low levels of cognitive load cause an external focus of attention and improve postural performance; however, when cognitive demands exceed one's cognitive capacity, dual-task interference is observed. Moreover, increasing cognitive load causes greater prioritization of the postural task (i.e., more deficits to cognitive performance). Visual stimuli appear to be more beneficial for stabilizing static posture compared to auditory stimuli, and articulation of the cognitive task appears to be more detrimental to posture compared to silent responding. Adapting the physical complexity of the dual-task has also been shown to interfere with the level of dual-task interference observed. Specifically, the preparatory and response phases of a large perturbation appear to require greater attentional control, which shifts attention away from the cognitive task in order to prioritize postural performance (i.e., slower reaction times, faster CoP latencies). Finally, reducing or modifying sensory information (e.g., visual input, somatosensory cues) increases attentional demands, leading to worse cognitive and postural dual-task performance, particularly in older adults. The effect of sensory conflict on postural performance in older adults may be due to reduced inhibitory control that is required to ignore incorrect sensory cues and readjust posture. Importantly, older adults may learn to flexibly allocate attentional resources to either prioritize cognitive performance under stable postural conditions or to prioritize postural performance when somatosensory information is compromised. Together, this research points to cognitive involvement in postural control, which becomes more apparent under conditions of greater postural threat and in the aging population.

While there is a corpus of evidence suggesting that dual-task walking increases the sensitivity in detecting fall risk and cognitive impairment in older adults, the research in the postural literature is more scarce. This may be due to the fact that balance assessments are more complex than gait assessments, particularly when using force platforms or assessing dynamic posture, which may make it difficult to complete in a clinical setting. Nevertheless, it is clear that adding a secondary cognitive task to a balance task exacerbates the level of dual-task interference observed in older adults with MCI or a history of falls. As such, this is an important area of research that needs to be further examined. Finally, there is evidence that as little as five sessions of cognitive dual-task training (Bherer et al. 2005) can improve dual-task balance performance in healthy older adults (Li et al. 2010); however, there is evidence to suggest that exercise training alone does not have noteworthy benefits on static or dynamic dual-task balance in older adults (see Gobbo et al. 2014 for review). Nevertheless, a growing field of research has integrated the results from the dual-task literature in order to build multi-modality interventions to improve other functional outcomes, with promising results (e.g., Timed-Up-and-Go; Desjardins-Crépeau et al. 2016; Li and Bherer 2019).

4 General Conclusions and Outlook

The substantial research on multiple-task performance, healthy aging, and pathological aging provide several insights that are either exclusively relevant to cognitive multitasking or across domains and elucidate the coordination of cognitive and motor processes that support cognitive–motor dual-tasking. Certainly, the work on aging and cognitive multitasking has a longer history of theoretical and empirical development compared to the motor dual-task literature. Given that the cognitive and motor multitasking works of literature have developed separately in a staggered fashion, we attempt some integrative conclusions to tie together these works of literature and offer potential future directions for research on aging, multitasking, and health implications.

From the aging and cognitive multitasking research, the major focus has been on understanding the locus of age-related declines in task switching and dual-task performances. Within the task-switching literature, the general consensus is that in healthy older adults and those with cognitive impairment, the processes required to hold more than one task set in working memory during mixed blocks of trials (global switch costs) are more vulnerable to aging than the processes required to rapidly alternate between task sets (local switch costs). However, with increasing levels of cognitive impairment, or substantial working memory demands, it is possible to observe significantly larger local switch costs in older than in younger adults.

The research on simultaneously performing multiple tasks (i.e., dual-tasking, multitasking) echoes the capacity-based explanation for age-related decreases in global switching performance. Specifically, investigations of cognitive dual-task performance in typical aging reveal a specific age deficit in dual-task coordination that cannot be fully explained by age-related general slowing. Deficits in task coordination are sporadically found in those with MCI and more robustly observed in those with AD. The technique of titrating or individually equating the difficulty of the single tasks has been used to rule out age differences in the component tasks as an explanation for observed deficits in dual-task performance. Other designs have focused on varying input or response modalities or have carefully manipulated stimulus onset times (the PRP paradigm) to uncover the locus of age-related interference effects during dual-tasking. These latter techniques explore other sources of age-related dual-task costs such as interference or neural overlap between tasks.

The logic of processing or neural overlap has been adopted in the movement sciences to better understand the increased cognitive involvement and cortical recruitment observed in typical and pathological aging during motor task performance.

While some aspects of cognitive dual-task methods have been adopted, such as the computation of dual-task costs and manipulations of cognitive load and modality, the motor aging research has less frequently examined dual-tasking with the level of temporal resolution used in cognitive multitasking experiments. Nevertheless, instructional variations in task emphasis have led to insights concerning older adults' ability to control their task priority, and methods such as EEG and EMG have allowed for good temporal resolution and understanding of when during a gait cycle, or when during recovery from a platform movement, cognitive processing is most interfering.

Looking forward, newer functional neuroimaging techniques that are tolerant to movement (e.g., fNIRS, high-density EEG) have very recently enabled more detailed understanding of the neural underpinnings of gait and posture under single- and dual-task conditions and show patterns of compensatory neural recruitment similar to those observed in the cognitive aging work. The use of laboratory simulations of real-life activities using VR or portable assessment techniques in the field will bring us closer to understanding everyday multitasking, which entails the dynamic integration of sensory, cognitive, and motor processes. Targeted cognitive training programs used either alone or in concert with physical training (particularly variable priority training) show promise in benefitting both cognitive and motor outcomes. Ultimately, understanding which specific cognitive processes are important for motor multitasking in old age will inform preventative and rehabilitative strategies to reduce fall risk and improve mobility and independence in older adults with and without cognitive impairment.

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Rachel I. Downey is a PhD student in Clinical Psychology. Her research focuses on ways to improve dual-task performance (i.e., walking and thinking) in healthy older adults and individuals with mild cognitive impairment through different forms of interventions (e.g., aerobic exercise, resistance training, gross motor coordination training, executive function training). She is also interested in how hearing ability influences and how effective different interventions are in improving dual-task performance, particularly in older adults who wear hearing aids. She also uses brain imaging techniques (i.e., functional near-infrared spectroscopy) to examine how the brain changes after cognitive or physical training while dual-tasking.

Music Training, Dance Training, and Multitasking

Melody Wiseheart

1 Introduction

Many skills and abilities have the potential to produce improvements in seemingly unrelated tasks. For example, some evidence exists that bilinguals have greater task-switching ability than monolinguals (Gunnerud et al. 2020). Training in Tai Chi Chuan has shown multitasking benefits (Wu et al. 2018), as has video game training (Pallavicini et al. 2018). Any number of skills might be associated with, or cause, multitasking improvements. The goal of this review is to investigate two acquired skills: music and dance.

Theorists have posited similarities between language and music structures (Feld 1974; Jackendoff 2009). Likewise, language and dance share structures (Hanna 2001), as do music and dance (Hanna 1982). Given that bilinguals seem to show improved multitasking performance (Gunnerud et al. 2020), and given the similar skills involved in bilingualism, music, and dance, one might expect to see multitasking benefits because of music and dance training. On the other hand, evidence exists that bilingualism is not, in fact, associated with improved multitasking performance (Moradzadeh et al. 2015), and thus one might not expect to see music and dance training benefits to multitasking. Nonetheless, all three constructs involve fine motor control skills, ability to parse and generate content within a prescribed structure, and connection between visual, auditory, and kinesthetic systems.

Music is the art of producing and combining sounds to produce an aesthetic or emotional effect. Music expertise takes many forms, as there are myriad instruments: woodwind, brass, string, percussion, vocal, and computer-generated sound. Learning each instrument involves the development of a set of technical skills over a long period of time. Thus, calling someone a musician indicates that the individual has some degree of music expertise in some subset of all possible music skills.

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Individuals develop expertise in specific genres of music, and each genre has its own set of rules (with a between-genre overlap in some skills and other genre-specific skills). Thus, like bilingualism, music expertise is heterogeneous, with wide variation in which skills are trained.

Recent meta-analyses investigated whether music training benefits cognitive skills (Cooper 2020; Gordon et al. 2015; Sala and Gobet 2019, 2020). The conclusion of these reviews is that music training rarely benefits performance across a wide range of cognitive tasks and that benefits of music training are small in magnitude. These reviews left out the literature on task-switching and dual-task performance, leaving open the question of whether multitasking benefits from music training. This omission is surprising because multitasking is at the core of music performance and thus is more likely than other cognitive skills to become highly trained during learning of music skills.

1.1 Skills Involved in Musical Performance

1.1.1 Shifting Attention

Musicians regularly shift attention between musical elements, including notes, rhythms, keys,[1] tempos, and dynamics (Moradzadeh et al. 2015). A core skill of musicianship is shifting attention between these and other performance elements. The confluence of which notes are sounded, when, and how loudly they are sounded form the basis of music. In a sense, each piece of music is a different task, containing its own combination of key, tempo, rhythm, and melody.

In music-making, attentional shifts take place using both internal and external sources (stylistic choices and memory of the piece; auditory feedback and bandmate cues). This is similar to task-switching paradigms (holding in mind when a task change should take place; visual cues to change task). Musicians maintain mental representations of the music (McPherson 2005), which is similar to the maintenance of task sets in computerized task-switching paradigms. Musicians must gracefully recover from mistakes, using auditory feedback, as occurs in many task-switching paradigms.

In many ways, attentional shifts between musical elements are unlike a typical task-switching paradigm. Musicians attend to these elements simultaneously, making music performance a form of simultaneous multitasking. Switching between songs does not involve an independent set of skills since the same core set of musical elements is involved. Unlike a typical laboratory task-switching paradigm, music performance involves lengthy practice (although musicians perform and learn many new, initially unpracticed pieces of music, so not all musical performance is highly practiced).

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[1] Music involves a set of notes that, in relation to each other, sound more harmonic or dissonant. Western music is based on musical keys, which are a prescribed set of standard notes.

1.1.2 Multitasking

Musicians integrate visual, tactile, and auditory information in real time (McPherson 2005; Moradzadeh et al. 2015; Wan and Schlaug 2010). This includes visual cues from sheet music and the physical keys (e.g., on a piano) or neck[2] of an instrument, tactile feedback from fingers, feet, and the respiratory system, and the sound of what is being produced by each musicians' actions. Music-making requires attention to one's part while simultaneously attending to the performance of other people in the ensemble to coordinate performance across the entire ensemble (Hasty 2004; Loehr and Palmer 2011; Loehr et al. 2013). Conducting requires the formation of a mental representation of the score[3] and guidance of decisions about performance in real time based on incoming auditory and visual information (Chaffin 2011). When errors occur, many conductors shift their attention to the error and generate a resolution, while simultaneously keeping track of where the score is going. At least while learning a piece, singing can be considered a dual task (Racette and Peretz 2007). Likewise, many dual-task paradigms require cross-sensory attention to simultaneously respond to multiple streams of information.

Over time, musicians develop increased sensitivity to details of musical structure (Palmer and Drake 1997), which could reflect improved multitasking skills. Production becomes more automatic, facilitated by performance cues (Chaffin and Logan 2006). Perception and action are more effectively coordinated (Pfordresher 2006). The combination of these skills could help musicians more effectively develop accurate, automatic responses in a dual-task paradigm.

1.1.3 Other Skills

Musicians practice general skills that might be helpful to laboratory task performance, such as error detection (Palmer and Drake 1997) and the ability to act flexibly in the face of unpredictable events (Geeves et al. 2014). Other practiced skills might be less relevant to multitasking, such as synchrony of movement (Repp 2006), efficient chunking skills to facilitate access of information from working memory (Geeves et al. 2014), control and precision of timing, consistency of performance, and planning (Janzen et al. 2014; Palmer 1997).

1.2 Methodologies

Two major methodologies have been used to investigate music and dance training effects on cognition. Most of the literature is experimental but correlational, comparing individuals with many years of music expertise, either instrumental or vocal,

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[2] The location on stringed instruments where fingers are placed in order to sound notes.

[3] A visual representation of a piece of music; also known as sheet music.

to controls who are not music experts. The largest advantage of these studies is the use of musicians and dancers with many years of expertise, which increases the likelihood of finding training effects. One downside is that it is difficult to find matched participants for the control group, who are identical to the experimental group on all factors except expertise. For the most part, researchers attempt to match samples on a range of background factors, such as age and socioeconomic status, but it is impossible to match all participant factors, such as level of interest in music.

A strong test of whether music-making produces changes in performance requires an experimental design in which there is random assignment into music training and control groups. The strength of this design is that potential confounding factors can be controlled; the downside is that experimental studies tend to be short, with at most months or a few years of music training. It is possible that many years of music training are needed before cognitive benefits can be detected.

While most studies compared groups with and without expertise, a few studies examined individuals with different degrees of expertise, such as those assigned to a music training group who have one, two, or three years of training, or individuals with varying hours of professional work experience. A couple of studies have examined correlations between objective measures of musical skill—such as pitch perception and rhythm discrimination—and cognitive skill.

1.3 Near and Far Transfer

While music training is obviously useful for the task of music-making, it is not a given that music training will improve other types of skills. If training works, it could improve skills that are quite similar (i.e., near transfer), such as memory training producing benefits on a different memory task. When tasks share common features between the source and target domain, as is likely to happen for similar tasks, the likelihood of transfer is increased (Thorndike and Woodworth 1901).

Alternatively, training could improve more distant skills, such as memory training improving general processing speed. This is called far transfer (Barnett and Ceci 2002). One theory of transfer divides tasks into a set of production rules, some of which are task specific, and others of which are general (Taatgen 2013). To the extent that these rules are involved in both tasks, even if the tasks appear to be dissimilar, transfer will occur. Theories of skill acquisition nearly always make predictions that far transfer can be achieved, despite the rarity of far transfer successfully occurring (Sala et al. 2019).

Unsurprisingly, near transfer is much easier to find than far transfer (Melby-Lervåg and Hulme 2013). In fact, there is debate in the training literature whether far transfer effects exist (De Simoni and von Bastian 2018; Guye and von Bastian 2017). Recent meta-analyses provide nuanced data on when and to what extent training programs show near and far transfer. Combining these meta-analyses, Sala et al. (2019) conducted a second-order meta-analysis of training programs. This analysis increases the accuracy of effect size estimates by reducing sampling error

(Schmidt and Oh 2013). After correcting for publication bias and the placebo effect, there was zero effect of training on far transfer across a wide range of domains, including music training.

Music production heavily relies on processing multiple streams of information and switching attention between incoming stimuli, which makes these skills obvious possibilities for far transfer. Even so, previous meta-analyses have not examined whether music training transfers to task-switching or dual-task performance.

2 Experts Compared to Imperfectly Matched Controls

Studies that involve music and dance experts, who have many years of training, provide the greatest opportunity to observe training benefits (Table 1). These studies account for the possibility that many years of training might be required before far transfer to cognitive benefits occurs. Typically, these studies sample individuals with existing expertise, along with a control group of individuals who have not trained in music or dance. The control group cannot be matched on every single background factor, making this a liberal test case for the possibility of training benefits but not definitive evidence that training alone is responsible for any observed benefits. These studies are quasi-experimental, not randomized controlled trials.

While many music expertise studies have shown training benefits, researchers have questioned the validity of the conclusion that music expertise causes cognitive benefits. Once background factors and music aptitude are statistically controlled, music expertise benefits often disappear (Schellenberg 2016; Swaminathan et al. 2017; Swaminathan and Schellenberg 2018, 2019). The question is whether task-switching and dual-task performance show robust benefits in music experts.

2.1 Task Switching

The most highly controlled task-switching paradigms investigate local and global switch costs, typically using tasks in which the participant must alternate between two task sets, such as parity (even or odd) and letter type (consonant or vowel). Local switch cost is the comparison of switch and nonswitch trials within blocks that involve task set alternation, while global switch cost is the comparison of non-switch trials in blocks that have a single task set or in which alternation takes place (Kiesel et al. 2010; Koch et al. 2018).

Evidence fails to suggest that musicians benefit at task switching, namely, local or global switch costs. Moradzadeh et al. (2015) used one of the largest sample sizes in this review chapter and found inconclusive results due to a lack of baseline matching (despite the large sample size). Two other studies with large sample sizes failed to find improvements in local switch costs with increasing years of training (Okada and Slevc 2018; Slevc et al. 2016). The remaining studies measuring local and global switch costs contained confounds that limit the interpretation of results.

Table 1 Studies comparing a group with music or dance training to a nonmusically trained group

Paper	Age (years)	Sample size	Music training	Control group	Task(s)	Measure(s)	Results
Wang et al. (2019)	17	96	Dong ethnicity: Song is integral to culture	Han ethnicity: Song is not part of culture	Pitch detection (bass or treble); timbre detection (wind or string); predictable switching	Local switch cost	Smaller local switch cost in Dong ethnicity
Wang et al. (2019)	17	96	Dong ethnicity: Song is integral to culture	Han ethnicity: Song is not part of culture	Parity (even or odd); letter type (consonant or vowel); predictable switching	Local switch cost	Smaller local switch cost in Dong ethnicity
Moradzadeh et al. (2015)	18–31	153	6–22 years of formal training	Yes	Numerical quantity (one or three items); numerical identity (numeral 1 or 3); predictable switching	Local and global switch cost	Larger local and global switch costs in musicians; results difficult to interpret because groups were not baseline matched
Slevc et al. (2016)	18–32	96	Continuous range from nonmusician to 5+ years of training	Yes	Parity (even or odd); letter type (consonant or vowel); predictable switching	Local switch cost	No relationship between the level of music training and local switch cost
Slevc et al. (2016)	18–32	96	Continuous range from nonmusician to 5+ years of training	Yes	Pitch detection (bass or treble); timbre detection (wind or string); predictable switching	Local switch cost	No relationship between the level of music training and local switch cost
Okada and Slevc (2018)	17–22	150	Continuous measure of music training using general undergraduate sample	Yes	Parity (even or odd); letter type (consonant or vowel); predictable switching	Local switch cost	No relationship between the level of music training and local switch cost

Paper	Age (years)	Sample size	Music training	Control group	Task(s)	Measure(s)	Results
Hesterman et al. (2019)	18–30	32	~5 years of music lessons	Yes	Tapping consistency; switch vs. nonswitch blocks; predictable switching	Global switch cost	Musicians showed better performance during switch blocks; this could be due to better memory for longer musical phrases
Saarikivi et al. (2016)	9–15	90	Mean training start age of 7 years old	Yes	Trail making test B	Trails B performance	Nonsignificant group difference
Bialystok and DePape (2009)	18–35	71	Mean of 16 years experience (half instrumental; half vocal)	Yes	Trail making test B	Trails B performance	Nonsignificant group difference
Hou et al. (2014)	~20	88	Mean training start age of 5 years old	Yes	Trail making test B	Trails B performance	Nonsignificant group difference
Bugos and Mostafa (2011)	~19	30	~9.5 years of music lessons	Yes	Trail making test B	Trails B performance	Musicians showed better performance
Hanna-Pladdy and Gajewski (2011)	59–80	70	10+ years music experience	Yes	Delis–Kaplan executive function system	Trail making test	Nonsignificant group difference
Zuk et al. (2014)	18–35	45	Mean training start age of 6 years old	Yes	Delis–Kaplan executive function system	Trail making test	Nonsignificant group difference
Zuk et al. (2014)	9–12	39	Mean training start age of 6 years old	Yes	Delis–Kaplan executive function system	Trail making test	Musicians showed better trail making performance
Strong and Midden (2020)	65+	57	1–20 years of private music lessons	Yes	Delis–Kaplan executive function system	Color-word interference task 4	Active musicians showed better performance than former musicians or nonmusicians

(continued)

Table 1 (continued)

Paper	Age (years)	Sample size	Music training	Control group	Task(s)	Measure(s)	Results
Strong and Mast (2019)	~73	58	Varied, with most participants having some history of private lessons	Yes	Delis–Kaplan executive function system	Color-word interference task 4	Musicians showed better performance
Clayton et al. (2016)	20–29	34	10+ years of formal training	Yes	Delis–Kaplan executive function system	Color-word interference task 4	Nonsignificant group difference
Hanna-Pladdy and Gajewski (2011)	59–80	70	10+ years music experience	Yes	Delis–Kaplan executive function system	Category switching fluency	Nonsignificant group difference
Mannermaa (2017)	13–20	59	Began training 4–7 years old	Yes	NEPSY-II	Arrow task	Nonsignificant group difference
Saarikivi et al. (2016)	9–15	90	Mean training start age of 7 years old	Yes	NEPSY-II	Arrow task	Musicians showed better performance
Degé et al. (2011)	9–12	90	1+ years of music lessons	Yes	NEPSY-II	Set-shifting task	Correlation between months of music lessons and set shifting (but correlation may be uninterpretable because one-third of participants had no music lessons, violating the continuous data requirement of the statistical test)
Robertson (2019)	14–18	40	3+ years of music training	Yes	Wisconsin card sorting test	Perseveration score	Nonsignificant group difference
Schellenberg (2011)	9–12	106	2+ years of music lessons	Yes	Wisconsin card sorting test	Perseveration score	Nonsignificant group difference
Hanna-Pladdy and Gajewski (2011)	59–80	70	10+ years music experience	Yes	Wisconsin card sorting test	Perseveration score	Nonsignificant group difference

Paper	Age (years)	Sample size	Music training	Control group	Task(s)	Measure(s)	Results
Sirisumthum et al. (2015)	18–24	40	Studying in a music program	Studying in a nonmusic program	Wisconsin card sorting test	Perseveration score	Nonsignificant group difference
Cocchini et al. (2017)	19–38	40	4–20 years of private instrument lessons	Yes	Visual pattern test and music recognition task	Percent change from single to dual task	Nonsignificant group difference
Douglas and Bilkey (2007)	~22	34	5+ years of music training	Yes	Pitch discrimination and either mental rotation or animal matching	Dual task relative to a single task baseline	Means show no evidence of a group difference
Walker et al. (2014)	18–24	66	Self-reported as a musician	Yes	Are beat tracks on or off the beat of music tracks (primary); track a moving dot by moving a cursor (secondary) or determine if a dot changed color (secondary)	Beat judgment accuracy	Interaction between training and secondary task type, with musicians outperforming nonmusicians on the primary task only when the secondary task was motor; nonsignificant group difference on secondary tasks
Walker et al. (2014)	18–28	70	Self-reported as a musician	Yes	Determine if three notes are the same or different (primary); track a moving dot by moving a cursor (secondary) or determine if a dot changed color (secondary)	Pitch judgment accuracy	Musicians outperformed nonmusicians at the primary task; nonsignificant group difference on secondary tasks
Moradzadeh et al. (2015)	18–31	153	6–22 years of formal music training	Yes	Motor tracking and letter detection	Dual task relative to a single task baseline	Musicians were more accurate

(continued)

Table 1 (continued)

Paper	Age (years)	Sample size	Music training	Control group	Task(s)	Measure(s)	Results
Moradzadeh et al. (2015)	18–31	153	6–22 years of formal music training	Yes	Auditory and visual n-back	Dual task relative to a single task baseline	Musicians were more accurate
Lim et al. (2001)	19–62	78	7+ years of formal music training	Yes	Melody comparison simultaneous with finger tapping	Melody comparison accuracy	Musicians were more accurate
Patston and Tippett (2011)	~24	72	10+ years of formal music training	Yes	Grammar checking simultaneous with one of three conditions (music with errors, music without errors, or no music)	Grammar checking accuracy	Musicians outperformed nonmusicians in the correct music and no music conditions
Patston and Tippett (2011)	~24	72	10+ years of formal music training	Yes	Visual search simultaneous with one of three conditions (music with errors, music without errors, or no music)	Visual search accuracy	Musicians outperformed nonmusicians in all three conditions
Escobar et al. (2020)	18–28	49	10+ years of formal music training	Yes	Dual task (auditory sentence plus noise) and single task (visual sentence without noise)	Word recall accuracy difference between single- and dual-task conditions	Nonsignificant group difference

For example, Wang et al. (2019) conducted task-switching studies that examined the Dong ethnic group in China. This ethnicity has a great deal of music expertise, as song is an integral part of their life. Some people in this ethnic group have expertise in singing Dong songs, which provide a means of transmitting culture between generations, while others do not sing these songs. Dong songs are polyphonic and sung a capella; they have harmonic and tonal complexity. In contrast, individuals of Han ethnicity are not familiar with Dong songs, as they speak a different language, and music is not an integral part of Han culture. This study, while notable, confounded cultural differences with differing degrees of music expertise.

The Trail Making Test Part B (Trails B) requires participants to draw lines between numbers 1–13 and letters A to L in ascending sequence (Reitan 1958). The Delis–Kaplan Executive Function System (D-KEFS; Delis et al. 2004) includes a similar trail making task, and it was shown to be equivalent to Trails B in a factor analysis (Atkinson and Ryan 2008; Delis et al. 2004).

Of the seven studies that investigated trail making test performance, only two showed a musician benefit. These two studies used small sample sizes, and the evidence suggests that these two studies were outliers, as four studies with double or triple the sample size failed to find a musician benefit. Notably, trail making test studies used participants from across the lifespan, from childhood to older adulthood, suggesting that the presence or absence of a music training benefit is not related to age.

There are significant issues with the trail making test as a measure of task switching. The trail making test involves shifting attention between letters and numbers, maintaining a mental record of the last letter and number used, and a significant visual search component, as the participant must locate circles with the appropriate character. Maintaining the proper sequence of letters might be less challenging for musicians, who are used to naming the letters A to G as indicators of musical notes. As a result, the task might be easier for musicians due to a factor that has nothing to do with task switching. In general, it is difficult to know if any observed advantage at Trails B performance is due to task switching, or another component of task performance.

The trail making test does not measure baseline performance on all task components individually (i.e., both number and letter sequence-making). Thus, this task fails to measure baseline performance against which switch performance can be measured. Trails B is measured as a time-to-complete score. Incorrect performance results in a tester prompt to correct the error, which results in the time score also including error correction time.

The D-KEFS includes a task that combines Stroop and task switching, with task changes between naming ink color and color word. Thus, this measure combines inhibition and task switching (cf. MacLeod et al. 2003, who argue that Stroop might not, in fact, be an inhibition task; note that no single task is a pure measure of an entire construct). There was evidence for a musician benefit on the Color-Word Interference Task 4 in older adults (Strong and Mast 2019; Strong and Midden 2020). It is not possible to determine if the musician benefit was related to inhibition or task switching.

Three other set-shifting measures (D-KEFS category switching fluency, NEPSY-II set-shifting task, and Wisconsin Card Sorting Test) failed to show a musician benefit, across six studies, despite some studies using a reasonably large sample size. The category switching fluency task of the D-KEFS involves switching between naming exemplars of two different categories of objects. This task combines retrieval of semantic knowledge and set switching. The NEPSY-II set-shifting task involves sorting animal cards into as many categories as possible, with a maximum of 12 possible categories. This task requires category generation skills in addition to sorting ability. The Wisconsin Card Sorting Test (WCST) requires participants to sort card into piles based on the number, shape, and color of geometric objects printed on the cards (Berg 1948). The sorting rule is changed after 10 correct sorts. The WCST requires problem-solving to determine the next task rule, as well as efficient working memory to keep track of which task rules have and have not been tried. As a result, performance on this task involves factors that are not related to task switching, making the common interpretation of this task as a measure of set shifting incorrect (Cepeda et al. 2000). Like the trail making tests, the WCST does not provide baseline performance measures. The WCST is untimed, so only accuracy scores are available. Researchers use the perseveration score as a measure of task switching.

Two studies have used the NEPSY-II arrow task, which involves naming the direction of an arrow, or the opposite direction, depending on arrow color (Brooks et al. 2009). This task is not a controlled task-switching measure because one of the component tasks requires inhibition, and there is no correction for this additional task component. This task produced inconsistent results across studies. Overall, scant evidence exists that music expertise is related to task-switching performance.

2.2 Dual-Task Performance

In general, quasi-experimental studies showed a musician advantage at dual-task performance, with five studies showing a musician benefit and three studies failing to do so. In particular, the studies that showed a musician benefit used relatively large sample sizes, whereas those that failed to find a benefit used smaller sample sizes, raising the possibility that the lack of a significant difference was due to insufficient sample size.

3 Differing Degrees of Expertise or Training

Some studies had no control group and instead examined music or dance experts with greater or fewer years of training or higher or lower performance on objective measures of music expertise (Table 2). Potentially, these studies provide stronger evidence than studies of music experts in comparison to controls because all individuals chose to partake in music or dance training.

3.1 *Task Switching*

The size–shape–color variantof the Dimensional Change Card Sort test involves the placement of cards into bins as indicated by a cue (Cepeda and Munakata 2007; Deák and Wiseheart 2015). This task, which is appropriate for young children who might not be able to complete a complex computerized task-switching paradigm, only has switch trials.

Janurik et al. (2019) examined the Dimensional Change Card Sort test performance of first-grade students, all musically trained using the Kodály[4] method. There was no control group. Five objective music perception tests (melody, pitch perception, chord analysis, rhythm discrimination, and tempo discrimination) were moderately correlated with task-switching performance, using the moderately difficult version of the card sorting task (Józsa et al. 2017). This study was notable in its use of large sample size and that it measured correlations between task-switching and objective measures of music ability rather than music training. While the study fails to contribute to the knowledge of whether task-switching skill improves because of training, it is useful to know that individuals who are good at task switching are also better at music skills.

Wood (2016) conducted a study on clef switching in musicians without a control group. Participants switched between playing triads in the treble and bass clef, with a clef change every two trials. Key signature changed every two blocks of 40 trials. Clef-switch trials were slower than clef-repeat trials, and initial trials in key signature change blocks were slower than later trials. The level of music ability did not predict switch cost. Music performance itself appears to involve a local switch cost, based on these two indicators.

3.2 *Dual-Task Performance*

It seems clear that having a large sample size is not sufficient to produce conclusive results. Jones (2006) compared musicians majoring in music or another field. Despite a sample size of 192 participants, Jones found a complex set of dual-task results that cannot be interpreted. Future studies need to use an objective measure of music expertise, which is a more nuanced measure of one's degree of musicianship than the choice of major.

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[4] A form of music training based on solfège, which is a movable pitch range with a name for each individual pitch. This form of music training emphasizes rhythm and movement in a social environment.

Table 2 Studies using individuals with differing levels of music expertise without a nonmusically trained control group

Paper	Age (years)	Sample size	Music training	Control group	Task(s)	Measure(s)	Results
Janurik et al. (2019)	7	131	8 months Kodály	No	Dimensional change card sort	Card sorting performance; five music perception tests (melody, pitch perception, chord analysis, rhythm discrimination, and tempo discrimination)	r = 0.26–0.45 between card sorting and music perception tests
Wood (2016)	18–74	22	Professional and hobbyist musicians	No	Clef switching; key signature switching	Local switch cost	Both groups showed a local switch cost for clef and key signature changes
Schneider (2018)	39–77	39	Current or former member of a professional orchestra	No	Trail making test B	Trails B performance; years of lessons, age began lessons, hours of practice, years worked for an orchestra, and type of instrument played	r = −0.09–0.19 between trails B and music experience measures
Jones (2006)	~21	192	Music majors and musicians not majoring in music	No	Visual image and auditory excerpt tasks (participants were asked if stimuli were novel)	Accuracy in dual- and single-task conditions	Complex interaction between major and condition (single vs. dual task), which is difficult to interpret
Wöllner and Halpern (2016)	18–73	30	Conductors and pianists who were professionals or students	No	Divided attention between two auditory streams	Detection of small timing or pitch variations	Experts and conductors were more accurate

Wöllner and Halpern (2016) compared more and less experienced conductors and pianists, all adults. The conductors also played piano, although they had fewer years of formal piano training than the pianists did. The paradigm involved dividing attention between two auditory streams and detecting small timing or pitch variations. Experts and conductors were more accurate at detecting target stimuli, which contained variations in timing or pitch. This study raises the possibility that different forms of music expertise could be related to the presence or absence of multitasking benefits. Replication of this study with a larger sample size would be useful, and it is not clear how much age-related factors played a role in producing observed conductor and expert benefits (since experts were older than students, and the age range included all of adulthood).

4 Experimental Training Studies

The strongest studies are randomized controlled trials, in which participants are randomly assigned into experimental or control groups (Table 3). If the sample size is reasonably large, any random differences between individuals will be equivalent for experimental and control groups so that more definitive statements about whether training benefits multitasking can be made. The major downside of these studies is that it can be challenging to collect a sample in which participants successfully complete a large amount of training, thereby maximizing opportunities to observe training benefits. Without lengthy training, it is not possible to rule out lack of sufficient training as an explanation for a lack of observed training benefit.

In contrast to most existing reviews, a meta-analysis by Meng et al. (2020) reported results of 13 dance training studies in relation to executive function, including a few that involved task switching. Similarly, Predovan et al. (2019) reported results for seven dance and cognition studies. Studies relevant to the current review are described, and specific task-switching effects are separated from effects of other executive functions.

4.1 Task Switching

Of the studies that used the best possible measures of task switching, either local and global switch cost or the trail making test, only one study found a musician benefit. Notably, the study that produced a training benefit (Bugos et al. 2007) was the only one to use individual rather than group training. It might be the case that individual instruction is more intense and thus more capable of producing a training benefit. However, this possibility seems unlikely. A case could be made that performing in a group more greatly taxes the executive function system and thus should be more likely to produce a benefit at multitasking. Also, other studies utilized intense training, in one case for several years, yet failed to show a training benefit.

Table 3 Randomized controlled trials of music or dance training

Paper	Age (years)	Sample size	Intervention	Training time	Control group	Task(s)	Measure(s)	Results
Alves (2013)	60–80	65	Group ballroom dance	Two 2-h sessions per week for 4 months	Walking or passive control	Quantity (larger or smaller than five)/parity (even or odd); predictable switching	Local and global switch cost	No group x time interaction
D'Souza and Wiseheart (2018)	6–9	75	Group music or dance training	Five 2-hour sessions per week for 3 weeks	Passive control (not randomly assigned)	Color (red or blue)/shape (cow or horse); unpredictable switching	Local and global switch cost	Local switch cost: Support for null hypothesis for both music and dance training; global switch cost: Inconclusive evidence
D'Souza and Wiseheart (2018)	6–9	75	Group music or dance training	Five 2-hour sessions per week for 3 weeks	Passive control (not randomly assigned)	Numerical quantity (one or three items); numerical identity (numeral 1 or 3); predictable switching	Local and global switch cost	Local and global switch cost: Support for null hypothesis for both music and dance training
Alves (2013)	60–80	65	Group ballroom dance	Two 2-h sessions per week for 4 months	Walking or passive control	Trail making test B	Trails B performance	No group x time interaction
Bugos (2010)	60–85	46	Group piano training	Weekly 45-min sessions for 16 weeks, plus 30 min of daily independent practice	Music listening	Trail making test B	Trails B performance	No group x time interaction

Paper	Age (years)	Sample size	Intervention	Training time	Control group	Task(s)	Measure(s)	Results
Bugos (2019)	60–80	135	Group piano training or group percussion ensemble	Weekly 45-min sessions for 16 weeks	Music listening	Trail making test B	Trails B performance	No group x time interaction
Bugos et al. (2007)	60–85	31	Individual piano instruction	Weekly 30-min sessions for 6 months, plus 3 h of independent practice per week	Passive control	Trail making test B	Trails B performance	Improvement in experimental but not control group, with training
Doi et al. (2017)	~76	172	Group ballroom dance or percussion playing	Weekly 60-min sessions for 40 weeks	Health education	Trail making test B	Trails B performance	No group x time interaction
Hackney et al. (2015)	~83	52	Group tango classes	Twenty 90-min sessions over 3 months	Classes on well-being and general scientific advances	Trail making test B	Trails B performance	No group x time interaction
Holochwost et al. (2017)	6–13	265	Orchestral music education	Five 2-h sessions per week for 39 weeks, for 1–3 years	Passive control	Trail making test from Atkinson and Ryan (2008)	Trails performance	No effect of number of years of music training
Kim et al. (2011)	~68[a]	38	Group dance (cha-cha)	Twice weekly 60-min sessions for 6 months	Passive control (not randomly assigned)	Trail making test B	Trails B performance	No group x time interaction

(continued)

Table 3 (continued)

Paper	Age (years)	Sample size	Intervention	Training time	Control group	Task(s)	Measure(s)	Results
Lazarou et al. (2017)	55–75^b	129	Group ballroom dance	Twice weekly 1-h sessions for 10 months	Passive control	Trail making test B	Trails B performance	Group comparison data and analyses were not reported
Merom et al. (2016a)	Older adults	79	Group ballroom dance	Twice weekly 1-h sessions for 8 months	Walking	Trail making test B	Trails B performance	No group x time interaction
Merom et al. (2016b)	Older adults	424	Group folk or ballroom dance	Twice weekly sessions for a total of 80 h in 1 year	Passive control	Trail making test B	Trails B performance	No group x time interaction
Seinfeld et al. (2013)	60–84	29	Group piano training	Weekly lessons plus 45 min of individual practice for 4 months	Leisure activities (not randomly assigned or matched in piano learning interest)	Trail making test B	Trails B performance	No group x time interaction
Bugos (2019)	60–80	135	Group piano training or group percussion ensemble	Weekly 45-min sessions for 16 weeks	Music listening	Delis–Kaplan executive function system	Category switching fluency	No group x time interaction
Sachs et al. (2017)	6	56	Orchestral music education or sports (community soccer or swimming)	Seven hours per week for 2 years	Passive control (not randomly assigned)	NEPSY-II	Arrow task, with alternate stimuli (hearts and flowers)	No group x time interaction

Paper	Age (years)	Sample size	Intervention	Training time	Control group	Task(s)	Measure(s)	Results
Holochwost et al. (2017)	6–13	265	Orchestral music education	Five 2-h sessions per week for 39 weeks, for 1–3 years	Passive control	Wisconsin card sorting test	Number of perseverative errors	Improved performance with more years of music training
Kosmat and Vranic (2017)	69–88	24	Group dance (waltz)	Weekly 45-min sessions for 10 weeks	Group discussion of various topics (e.g., needs and interests of older adults)	Wisconsin card sorting test	Number of perseverative errors	Improved performance at post-test for the dance group but not for controls
Norgaard et al. (2019)	13–14	155	Jazz band; concert band class plus improvisation	Two months (no details on frequency or length of training, or whether total training time was matched between groups, were provided)	Concert band	Wisconsin card sorting test	Number of perseverative errors	No group x time interaction
Coubard et al. (2011)	60–89	110	Group contemporary dance or tai chi	Weekly 1-h sessions for 6 months	Fall prevention (not randomly assigned)	Behavioural assessment of the Dysexecutive syndrome	Rule shift cards test	Groups were not matched at baseline, so data cannot be interpreted

(continued)

Paper	Age (years)	Sample size	Intervention	Training time	Control group	Task(s)	Measure(s)	Results
Chen and Pei (2018)	~77[c]	25	Individual musical dual-task training (music therapy)	Weekly 60-min sessions for 2 months	Reading newspapers, playing chess and/or walking	Forward and backward digit recall while walking	Percent change in gait speed under dual-task vs. single-task conditions; percent change in stride length under dual-task vs. single-task conditions	No group x time interaction
Esmail et al. (2020)	~67	41	Group dance and movement or aerobic exercise training	Thrice weekly 1-h sessions for 12 weeks	Passive control	Two visual discrimination tasks	Single- and dual-task RT	No group x time interaction
Hamacher et al. (2015)	~68	35	Group dance training	Twice weekly 90-min sessions for 6 months	Exercise (endurance, strength, and flexibility)	Reciting serial three subtractions while walking	Serial subtraction speed; stride time variability; stride length variability; toe clearance variability	Greater improvement over time in serial subtraction speed and toe clearance variability in dance group; no group x time interaction for stride time or stride length variability

Note: [a] with metabolic syndrome; [b] with amnestic mild cognitive impairment; [c] with mild to moderate dementia

The other exception is a study that utilized the Wisconsin Card Sorting Test. Holochwost et al. (2017) found a benefit to Wisconsin Card Sorting Test performance after years of group orchestral training. Interestingly, they did not find a benefit to trail making test performance in the same sample. These inconclusive findings highlight the importance of measure selection since measures that tap multiple executive functions (e.g., the Wisconsin Card Sorting Test) might be more likely to demonstrate a training benefit.

4.2 Dual-Task Performance

No experimental music training studies were located in the literature (although one music therapy study was found that used a dementia sample). Thus, the literature consists primarily of dance training studies. All the studies that measured dual-task performance used older adults.

In contrast to the positive findings of an expertise benefit compared to imperfectly matched controls, for dual-task performance, the literature failed to support a dance training benefit to dual-task performance for randomized controlled trials. Notably, the lack of observed dual-task benefit could be due to the relatively small sample size used by existing randomized controlled trials.

5 Do Training Programs Work?

Several meta-analyses exist, which examined music training in relation to control groups using randomized controlled trials. A meta-analysis by Kim and Yoo (2019) investigated music instrument training effects on a variety of aspects of cognition in older adults. They found 10 studies of music interventions. Effects of music training on cognition were minimal, at best. Sala and Gobet (2017a, b, 2019, 2020) examined music training effects on a wide range of cognitive tasks. Their conclusion was that music training has near-zero benefits across tasks, especially when music training and active control groups are compared. A second-order meta-analysis showed that studies using passive control produced a small music training benefit, while those using active controls had no music training benefit (Sala et al. 2019). Likewise, the current review found little evidence of a training benefit to task-switching or dual-task performance.

5.1 Issues with Training Studies

Unlike trials of pharmaceuticals, it is not possible to blind participants to their experimental condition, so expectation effects could be present (Green et al. 2014). It might be possible to choose an active control group that negates this concern, such as a comparison of music and dance training (D'Souza and Wiseheart 2018). With an appropriate control group, expectation effects might be made equivalent between experimental groups.

Ideally, a control group would account for improvement due to mechanisms of no interest (Green et al. 2014; Von Bastian and Oberauer 2014). Commonly, active control groups account for factors such as experimenter attention, motivation, and engagement. Conversely, passive control groups fail to account for expectation and experimenter effects, which could affect post-trial test performance differences between groups (Morrison and Chein 2011). Studies that have an active control group showed a smaller music training benefit than those with a passive control group (Cooper 2020).

A more general concern is that each study uses its own conceptualization of the intervention of interest (Green et al. 2014; Morrison and Chein 2011). Not all music training programs include the same training elements. Some are purely instrumental and others include vocals; some are long and others comparatively brief. Music is a multidimensional construct (Cogo-Moreira and Lamont 2018), making it critical to ensure that evaluated cognitive skills overlap with trained music skills.

Test–retest effects can be a concern (Green et al. 2014). We know that task switching shows steep practice effects (Cepeda et al. 2001), and there might be less room for improvement in task performance at post-test compared to pre-test. These practice effects might make it challenging to detect a benefit of training, masking the presence of a true music training effect.

Not always discussed is that all training programs used in randomized controlled trials are brief in comparison to the amount of training needed to move from novice to expert skill level. When meta-analyses find that the literature does not appear to support training benefits, they are working from a definition of training that is short-term. The training literature is underpowered in the sense that short-term interventions are not a strong test of long-term music training effects. True music training effects might exist but be missed because studies do not measure performance changes across many years.

Few studies formally assessed the amount of improvement that took place during training. Yet the degree of training improvement predicted cognitive task performance (Jaeggi et al. 2011; Von Bastian and Oberauer 2014). Perhaps music programs did not show a training effect because the intervention only produced a small improvement in music skills. Or, perhaps some individuals in the sample showed a large training improvement and others did not, due to differences in trainee characteristics, such as motivation and self-efficacy (Burke and Hutchins 2007; Grossman and Salas 2011). That would lead to a reduction in training effect size since individuals who failed to show an improvement with training would reduce the potential for performance benefits on cognitive measures.

Training studies tend to measure intervention effects soon after the end of the training program, sometimes with a follow-up a year later. It is important to know whether training effects are long-lasting or only short-term (Melby-Lervåg and Hulme 2013). Articles often imply that training produces long-term benefits, but there is usually insufficient data to make this claim. If short-term benefits of music training are not found, it is unlikely that long-term benefits would suddenly occur. There is no reason to expect incubation effects, in which there are changes in a skill—such as problem-solving—after a break (Browne and Cruse 1988; Sio and Ormerod 2009).

Ideally, studies would utilize latent variables or multiple tasks to measure constructs, such as dual-task performance, rather than a single task, such as a specific dual-task paradigm (Noack et al. 2014; Shipstead et al. 2012). Doing so would result in less biased and more parsimonious estimates of a construct, as well as reduced measurement error (Spirtes 2001). Many studies in this review only included a single measure per construct, and almost none included a formal latent variable.

Only one study (D'Souza and Wiseheart 2018) used Bayesian analyses, which are capable of distinguishing null from indeterminate results. It is critical that studies of music and dance training update their analysis methods. Currently, it is not certain whether the many failures to find a training benefit are due to a true null effect or an insufficient sample size. If the true effect size for a music or dance training benefit is small, this effect would be missed by most previous research. That said, the sheer number of studies that failed to find a training benefit using randomized controlled trials—including a study with a large sample size and years of intense, formal music training—suggests that any music or dance training benefit is in fact small in magnitude.

5.2 General Conclusion

Until recently, it appeared that music training might improve performance on unrelated tasks, including task-switching and dual-task performance (Moradzadeh et al. 2015). However, randomized controlled trials of music and dance training suggest that training might not have an effect, especially compared to an active control group (Alves 2013; D'Souza and Wiseheart 2018). More research is needed—especially studies that use a long intervention of at least 6 months—since it appears likely that benefits of music training are only observed after substantial training time (Bugos et al. 2007; Holochwost et al. 2017).

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