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Exploring triple tasks: A deeper dive into multitasking dynamics

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Wie jede Blüte welkt und jede Jugend
Dem Alter weicht, blüht jede Lebensstufe,
Blüht jede Weisheit auch und jede Tugend
Zu ihrer Zeit und darf nicht ewig dauern.
Es muss das Herz bei jedem Lebensrufe
Bereit zum Abschied sein und Neubeginne,
Um sich in Tapferkeit und ohne Trauern
In andre, neue Bindungen zu geben.
Und jedem Anfang wohnt ein Zauber inne,
Der uns beschützt und der uns hilft, zu leben.

Wir sollen heiter Raum um Raum durchschreiten,
An keinem wie an einer Heimat hängen,
Der Weltgeist will nicht fesseln uns und engen,
Er will uns Stuf' um Stufe heben, weiten.
Kaum sind wir heimisch einem Lebenskreise
Und traulich eingewohnt, so droht Erschlaffen,
Nur wer bereit zu Aufbruch ist und Reise,
Mag lähmender Gewöhnung sich entraffen.

Es wird vielleicht auch noch die Todesstunde
Uns neuen Räumen jung entgegensenden,
Des Lebens Ruf an uns wird niemals enden…
Wohlan denn, Herz, nimm Abschied und gesunde!

—Hermann Hesse

Danksagung

Wie Hermann Hesse in seinem Gedicht "Stufen" treffend formuliert, markiert diese Schrift das Ende eines (akademischen) Lebensabschnitts – eines Abschnitts, der reich an neuen Erfahrungen und wunderbaren Begegnungen war. Ein Abschnitt, der ohne meinen Doktorvater Prof. Dr. Wolfgang Mack nicht möglich gewesen wäre. Unter seiner Anleitung durfte ich Ideen entwickeln, ausprobieren und umsetzen, durfte an ihnen scheitern, aus ihnen lernen und letztendlich Erfolg haben. Bei jedem Schritt fühlte ich mich bestärkt und gefördert. Diese Unterstützung ist in der Forschung, die leider oft von finanzieller Knappheit und Zeitdruck geprägt ist, keine Selbstverständlichkeit. Deshalb möchte ich an dieser Stelle, für immer festgehalten in Tinte, von ganzem Herzen sagen:

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Records of Achievement

Contribution 1

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Zusammenfassung

Multitasking, die Fähigkeit, mehrere Aufgaben gleichzeitig zu bewältigen, ist seit Jahrzehnten Gegenstand umfangreicher Forschungsarbeiten. Die meisten Studien haben sich jedoch auf Doppelaufgaben-Szenarien konzentriert, so dass eine erhebliche Lücke in unserem Verständnis darüber besteht, wie sich Individuen in komplexeren Multitasking-Umgebungen verhalten. Diese Dissertation soll diese Lücke etwas verkleinern, indem sie ein Dreifachaufgaben-Paradigma einführt, das die gleichzeitige Ausführung von drei Aufgaben beinhaltet: eine visuell-manuelle, visuell-pedale und auditiv-vokale Aufgabe.

Die erste Studie untersuchte die Leistungsdynamik des Dreifachaufgaben-Paradigmas und verglich diese mit den Einzelaufgaben- und Doppelaufgaben-Bedingungen. Die Ergebnisse zeigten, dass die Teilnehmer (N = 19) nach drei Sitzungen die besten Leistungen bei den Einzelaufgaben hatten, gefolgt von den Doppelaufgaben und der schlechtesten Leistungen bei der Dreifachaufgabe. Interessanterweise neigten die Teilnehmer dazu, die Hand- und Fuß-Aufgaben zu gruppieren und in den meisten Fällen gleichzeitig darauf zu reagieren. Diese Beobachtung deutet darauf hin, dass strategische Komponenten bei der Bewältigung mehrerer Aufgaben eine wichtige Rolle spielen und dass Aufgaben in Dreifach-Aufgaben-Szenarien hierarchisch strukturiert sein könnten.

Die zweite Studie untersuchte die Auswirkungen eines Doppelaufgaben-Trainings auf die Leistung bei drei Aufgaben über einen Zeitraum von bis zu 17 Sitzungen. Teilnehmer, die ein Doppelaufgaben-Training absolviert hatten (N = 13), zeigten eine Präferenz für die zuvor erlernten Reiz-Reaktions-Zuordnungen, während Teilnehmer ohne vorheriges Training (N = 14) die Hand- und Fuß-Aufgaben gegenüber der auditiven Aufgabe bevorzugten. Am Ende des Dreifachaufgaben-Trainings wiesen beide Gruppen signifikante Verbesserungen der Reaktionszeiten auf, obwohl die Zeiten in allen Aufgaben weiterhin höher waren als in Doppelaufgaben-Studien.

In dieser Dissertation werden die Herausforderungen bei der Auswahl geeigneter Aufgaben für ein Dreifachaufgaben-Paradigma, die Berechnung der Multitasking-Kosten und die Auswirkungen auf aktuelle Multitaskin-Modelle erörtert. Sie hebt die Grenzen aktueller Modelle hervor, insbesondere struktureller Modelle wie Engpassmodelle, und schlägt vor, dass Ressourcenmodelle bessere Vorhersagen für Dreifachaufgaben-Szenarien bieten könnten.

Diese Dissertation zeigt, dass Dreifachaufgaben-Paradigmen kognitive Ressourcen anders nutzen als wir es aus der Doppelaufgaben-Forschung kennen und unterstreicht somit die Notwendigkeit für umfassenderer Modelle, die die Komplexität der menschlichen Kognition in Multitasking-Szenarien berücksichtigen können. Zukünftige Forschungen sollten die Auswirkungen von Strategien, Aufgabenkombinationen und Asynchronität des Stimulusbeginns auf die Dreifachaufgaben-Leistung untersuchen, um die Lücke zwischen Ansätzen auf der Mikro- und Makroebene der Multitasking-Forschung weiter zu schließen.

Abstract

Multitasking, the ability to manage multiple tasks simultaneously, has been a topic of extensive research for decades. However, the majority of studies have focused on dual-task scenarios, leaving a significant gap in our understanding of how individuals navigate more complex multitasking environments. This dissertation aims to narrow this gap somewhat by introducing a triple-task paradigm, which involves the simultaneous execution of three tasks: a visual-manual task, a visual-pedal task, and an auditory-vocal task.

The first contribution explored the performance dynamics of the triple-task paradigm, comparing it to single-task and dual-task conditions. Results showed that participants (N = 19) performed best after three sessions on single tasks, followed by dual tasks, and worst on the triple task. Interestingly, participants tended to coordinate the manual and pedal tasks, responding simultaneously in most cases. This finding suggests that strategic components play a significant role in managing multiple tasks and that tasks may be structured hierarchically in triple-task scenarios.

The second contribution investigated the impact of dual-task training on triple-task performance over up to 17 sessions. Participants who had undergone dual-task training (N = 13) showed a preference for the previously learned stimulus-response mappings, while those without prior training (N = 14) favored the visual-manual and visual-pedal tasks over the auditory-vocal task. By the end of the triple-task training, both groups showed significant improvements in response times, although the response times remained higher than those observed in dual-task studies.

This dissertation discusses the challenges of selecting appropriate tasks for a triple-task paradigm, calculating multitasking costs, and the implications for current multitasking models. It highlights the limitations of current models, especially structural models like bottleneck models, and suggests that resource models may offer better predictions for triple-task scenarios.

This dissertation demonstrates that triple-task paradigms utilize cognitive resources differently compared to dual-task research, emphasizing the need for more comprehensive models that account for the complexities of human cognition in multitasking scenarios. Future research should explore the impact of strategies, task combinations, and stimulus onset asynchronies on triple-task performance to bridge the gap between micro-level and macro-level approaches to multitasking research further.

Contents

List of Figures

Introduction

"Multitasking" is a term that has become commonplace in our vocabulary. While it is often associated with human behavior, its roots are firmly planted in the field of computer science. In the early days of computing, only single-processor systems were feasible, prompting a quest for optimization strategies. One of the first computers known to possess multitasking capabilities was installed aboard the Apollo spacecraft. Its unique design and programming allowed it to execute multiple tasks concurrently through a process of task interruption. As technology advanced, computers were engineered with multiple processors, enabling tasks to be distributed among them. This concept is mirrored in human multitasking: if one can seemingly perform multiple tasks at the same time - simultaneously, this kind of performance is called multitasking. However, this brings us to the question of what constitutes "simultaneity". While most studies do not concretely define simultaneity, we can categorize multitasking within a *multitasking continuum* (Salvucci et al., 2009), ranging from the *sequential multitasking* to the *concurrent multitasking* . The *sequential multitasking* encompasses all tasks on a continuum that exceeds 10 seconds. The *concurrent multitasking* includes all tasks within 10 seconds (Salvucci et al., 2009).

Before we dive into the research on multitasking, it is crucial to clarify the meaning of the term "task". Notably, this term has no universally accepted definition, making assessing a given task's difficulty or complexity challenging. The lack of a precise definition further complicates the process of determining whether a task is inherently simple or complex and whether complexity correlates with difficulty. Therefore, I will provide a brief historical overview *Brief historical review* and delve into the complexities in detail in separate sections, *What is a task?* and *What makes a task "complex"*.

Following this, I will discuss the different levels of multitasking and their models in the section *The micro and macro level of multitasking*, and highlight the research gap between the micro (laboratory-based studies) and macro (application-oriented studies) levels. Most models originate from the micro level and are typically challenging to apply to real-world scenarios. To address this gap, this dissertation attempts to approach the macro side from the micro side using simple triple tasks, aiming to provide further insights.

I will also discuss various aspects of (dual-task) training and the subsequent possible (near) transfer effects to other tasks in the section *Dual-task training and transfer.* It should be noted that there is also - so far - no empirical evidence for more than two tasks within the micro level, and the possible implications for multiple tasks can only be explored theoretically. Furthermore, it is imperative to highlight the pivotal role of my research on triple-task scenarios within this context. My work significantly extends the current understanding of multitasking by exploring beyond the conventional dual-task paradigms. This exploration into the dynamics of handling three simultaneous tasks not only fills a critical gap in the existing literature but also represents a substantial advancement in our comprehension of cognitive load management and task prioritization. The insights gained from this research could potentially open new avenues for designing more effective training programs that cater to the complexities of real-world multitasking situations. Thus, the contribution of my work on triple tasks stands as a considerable gain in the field, pushing the boundaries of what we know about multitasking and its effects on cognitive performance.

Brief historical review

The human cognitive system does not possess infinite resources. The fundamental question of whether we can process multiple tasks simultaneously without a loss in performance has captivated researchers for over a century and remains an active area of investigation today. Early pioneers such as Telford (1931) and Welford (1952) were among the first to demonstrate that when individuals are required to respond to two successive stimuli, the response to the second stimulus is invariably delayed. Their results indicated that significantly more time was needed to respond to the second stimulus when both stimuli were presented sequentially, a concept known as stimulus onset asynchrony (SOA). The shorter the SOA, the longer the response time for the second stimulus. This occurs because as one stimulus is being processed, the second (or any subsequent stimuli) must wait, leading to a delay due to a hypothesized central bottleneck. These findings imply that the human cognitive system operates with a limited set of resources that need to be distributed accordingly. As a result, they posited that there is a single channel of cognitive processing that adheres to an all-or-nothing principle. However, this stringent perspective was challenged relatively quickly; for instance, when compatible stimulus-response (S-R) mappings are used, the response time for the second task is minimally affected, if at all (Greenwald & Shulman, 1973; Heuer, 1996). Compatible S-R mappings are e.g., visual-manual or auditory-vocal, while the combination the other way round is considered incompatible (more on this in section *What is a task?*).

In contrast to the single-channel theory, another approach posits the existence of a central capacity that must be allocated in a graded manner (Bornemann, 1942a, 1942b; Heuer, 1996). This leads to the subsequent question of how these resources are distributed. Kahneman (1973) introduced the theory of a single, limited attentional capacity that influences dual-task performance. According to Kahneman, attentional resources are allocated based on the demands of the tasks at hand. Expanding upon this, Norman and Bobrow (1975) proposed that task handling limitations are not solely due to cognitive resource constraints (resource-limited) but also to the availability of information (data-limited). As tasks increase in complexity, processing them becomes more challenging or even impossible. Furthermore, they suggested that a performance-resource function could be defined for each task, indicating that complex tasks limit the efficiency of resource allocation and processing capabilities, a notion that contrasts with Kahneman's theory of a singular attentional resource. In essence, the more efficiently a resource can be allocated, the greater the number of tasks that can be processed simultaneously. However, each task requires different resources (data-limited), which complicates processing. While the single-resource theory remains influential, the concept of multiple resources emerged relatively quickly. A still prevalent theory is the multiple resources theory by Wickens and Liu (1988), which is primarily based on observations of visual and auditory tasks. These tasks may or may not overlap in processing due to task similarities, with increased similarity leading to poorer performance (what the single channel model could not take into account). Although the basic considerations regarding task interference can be applied to other observations, the model's applicability is limited. Conversely, Posner (1980) advocated for a centralized (single) resource model, marking a departure from the previously suggested multiple resource theories. Posner's model suggests that attention operates as a singular, flexible system that can be directed by the individual rather than as a set of multiple, specific resources that could be independently allocated to concurrent tasks.

The theories discussed thus far have profoundly influenced our comprehension of cognitive resource allocation and multitasking. However, they primarily serve as historical milestones and represent just a fraction of the current models that continue to shape contemporary research. In the chapter *The micro and macro level of multitasking*, I will explore additional pivotal and relevant models in today's scholarly discourse. This exploration aims to provide a more detailed understanding of multitasking functions across both micro and macro dimensions.

To encapsulate the historical overview, it is evident that dual-task research has evolved from a primary focus on the cognitive system's limitations to a more sophisticated examination of how attentional resources are distributed and managed. Despite the diversity of tasks investigated in multitasking research, a common thread is their utility in formulating various theoretical assumptions. Echoing the insights of Norman and Bobrow (1975), the specific nature of a task is crucial in the process of information handling. The next chapter will further dissect this complexity by examining how the manipulation of key elements—namely instruction, stimulus, response, speed, accuracy, and strategy—impacts our ability to juggle multiple tasks. This detailed analysis will shed light on the intricate dynamics of multitasking, offering a richer perspective on its underlying mechanisms.

What is a task?

As we delve into this chapter, I encourage you to reflect on a seemingly straightforward task: your daily commute to work, which happens to be a short distance from your home. How do you navigate this routine? At first glance, the question may seem trivial, but upon closer examination, it reveals a range of decisions: Do you prefer to walk or select a particular mode of transportation? If walking is your choice, consider the speed at which you travel. Is your walking speed consistent each day? And do you take the most direct route or occasionally stop by a supermarket to pick up necessities? The variety of options available illustrates that even routine tasks can be approached in numerous ways. While this example is quite specific, it underscores a universally applicable principle, even to performing simple tasks in a laboratory setting. Typically, these tasks require repetition, often hundreds of times, and may span across multiple sessions. Classic tasks used to study multitasking in the laboratory are discrete choice response time tasks with fixed stimulus-response mappings and minimal planning requirements (Schumacher & Hazeltine, 2016), also called component tasks or task sets (Hirsch et al., 2021). For instance, if a circle (stimulus) appears on the right side of the screen, you should press a button with your hand on the right (response), and vice versa for the left side.

In his framework, Hackman (1969) noted that there is an objective task at hand, which in this case involves a circle (the stimulus), the instruction to respond to it with one of the buttons (the operational instruction), and the goal of doing this as quickly and accurately as possible (the goal-oriented instruction). However, the personal factors of the participant also come into play. These factors include understanding, acceptance, or previous experience with the task, as well as the participant's own abilities, motivation, and level of arousal. The task and the participant interact, and the outcome may not always align with the experimenter's assumptions. Very similar to the initial example, despite a routine, every commute to work is slightly different.

Two distinct elements can be identified in this context. Firstly, there is the task itself, which exists independently of the individual. Secondly, there is the goal, which is inherently tied to a specific person, as outlined by Künzell et al. (2018). However, in multitasking scenarios, participants are required to respond to not just one but two or more tasks. Nevertheless, when multiple tasks need to be handled, they can, in specific cases, be integrated into a single task by modifying the goal(s). This was demonstrated by Hazeltine et al. (2007) in training. They found that tasks independent of modality (for example, manual and vocal tasks) were chunked into high-order representation (Seibel, 1963) and therefore processed faster than separately from each other, unlike tasks dependent on the same modality (such as two manual tasks, which normally end in a response selection bottleneck).

An insightful framework called a task file, is introduced by Schumacher and Hazeltine (2016) (see also, Hazeltine & Schumacher, 2016). This concept builds upon the foundational ideas of object files, as defined by Kahneman et al. (1992), and the subsequent extension into event files by Hommel (1998). Object files represent cognitive constructs that encapsulate information about the properties and continuity of objects within the visual field, serving as a basis for tracking and identifying objects as coherent entities over time. Hommel (1998) expanded this notion to include not only the perceptual aspects of objects but also the actions associated with them, the goals driving these actions, and the broader context of the task at hand, thus introducing the concept of event files. Schumacher and Hazeltine (2016) take these ideas a step further with the task file framework. Unlike its predecessors, the task-file approach does not advocate for a single, universal method for response selection. Instead, it posits a decentralized network of processes, the nature of which is shaped by the specific characteristics of the task at hand. This framework suggests that factors such as motivation (drives), goals, actions (transformations), and motor codes play integral roles within task files, with all information being organized hierarchically. In essence, while object files focus on objects' static properties and continuity, and event files integrate these properties with actions and goals, task files encompass a broader spectrum. They not only integrate sensory and action-related information but also consider the motivational and goal-oriented aspects of task execution, offering a more comprehensive and dynamic representation of how tasks are cognitively processed and managed.

As suggested earlier, the complexity of a task often surpasses initial assumptions and requires clear understanding by the individual performing it. This is particularly true in the context of multitasking, where responses to multiple stimuli are required. The participant must have a comprehensive understanding of all actions involved. To reduce variance in execution and ensure that each participant thoroughly understands the tasks and rules, some form of practice or training is invariably necessary. It's also worth noting that participants may experiment with different strategies during the initial session. While this is not the primary focus of our inquiry, it is an inherent part of the true processing of multitasking tasks.

What makes a task "complex"

The work of Norman and Bobrow (1975) underscores that task performance is contingent on its complexity. Yet, the concept of a complex multitasking task lacks a universal definition. The characterization of task difficulty varies widely across disciplines and perspectives (for example, Aksentijevic & Gibson, 2012; McIsaac et al., 2015; Wood, 1986). The terms task complexity and task difficulty are frequently used synonymously, but they can be distinguished. The task itself determines task complexity, whereas task difficulty is influenced by the cognitive abilities and objectives of the participant (Robinson, 2001; Wood et al., 1987). As demonstrated in the preceding chapter, these two aspects are intertwined. Most studies attempt to keep task difficulty constant by using identical conditions, goals, and a homogeneous sample. However, task complexity is often given less attention. Thus, I will focus on task complexity in the following discussion. Wood (1986) divided complexity into, but not limited to, component and coordinative complexity. I suggest refining the notion of coordinative complexity by introducing intra-coordinative and inter-coordinative complexities, as coordination can occur both within (intra) and between (inter) tasks. Intra-coordinative complexity complements component complexity and is discernible even in single tasks (for example, Göthe et al., 2016; Hoffmann et al., 2019). Conversely, inter-coordinative complexity gains prominence in dual-task scenarios (e.g., Hirsch et al., 2017; Strobach, 2023). This type of complexity will be the focus of a more detailed discussion in the subsequent sections.

Component complexity is defined by unique task actions that require specific resources and do not overlap with others (Wood, 1986). This concept can be further nuanced. For instance, when a single task must be performed but multiple options are available, response time increases, as explained by the Hick-Hyman Law (see Seow, 2005). Conversely, redundancy among components can decrease complexity by creating overlap in task demands, thus reducing the need for specific knowledge and skills. Total redundancy is achieved when a task necessitates the repetition of the same action (Naylor & Dickinson, 1969). In the context of multitasking, complexity is lowest for single tasks and increases with dual tasks, escalating further as tasks exceed two, regardless of their nature. This increase in complexity is well-documented through research on the costs associated with performing dual tasks (refer to Koch et al., 2018; Pashler, 1994; Ruthruff et al., 2003; Tombu & Jolicoeur, 2004). However, it's important to note that complexity arises not just from the number of tasks but also from their specific characteristics (intra-coordinative complexity).

The execution of component tasks can vary, leading to increased response times and error rates, influenced by the stimuli (S) and responses (R) mappings employed (see, Koch et al., 2018; Pashler, 1994; Strobach, 2023), which relates to *intra-coordinative complexity.* Göthe et al. (2016) showed that the response time of dual tasks can be significantly affected by selecting compatible stimulus and response modalities (also see, Kornblum & Hasbroucq, 1990). The response times in dual tasks compared to single tasks could be entirely offset when both were compatible. Compatibility means a more or less natural fit between input and output. The fastest way to respond to visual tasks is by means of a manual response. This is also favored if the response to a stimulus with a right-hand characteristic (e.g., a circle on the right side of the screen) is also to be made with the right hand. Both the modalities and features must be suitable for an optimal response time. In conclusion, a significantly worse stimulus-response combination is, for example, when a visual stimulus with a right-hand characteristic has to be responded to with the voice by saying the opposite "left" (also see, Hazeltine et al., 2006; Maquestiaux et al., 2018; Stelzel et al., 2006). Schumacher et al. (2001) further demonstrated that compatible S-R mappings could eliminate additional costs with adequate training (more on this in the chapter *Dual-task training and transfer*).

Inter-coordinative complexity focuses on the management of simultaneous tasks. Research on dual-task training reveals that coordinating two tasks presented at the same time requires specific skills, unlike training for a single task (Liepelt, Strobach, et al., 2011; Strobach, Frensch, et al., 2012). It has been found that improvements in dual-task performance are primarily due to enhanced execution of the second task, with only minor improvements in the first task (Ruthruff et al., 2003; Schumacher et al., 2001; Strobach, Frensch, Mueller, & Schubert, 2012; Strobach, Frensch, Müller, & Schubert, 2012; Tombu & Jolicoeur, 2004). According to the efficient task instantiation model proposed by Schubert and Strobach (2018), the advantage seen after dual-task training is linked to a faster switch between tasks. This advantage is due to the efficient activation of relevant task information in working memory at the start of a dual-task trial rather than at the commencement of each individual sub-task. Furthermore, Maquestiaux et al. (2004) demonstrated that this efficient instantiation occurs at the beginning of the dual-task trial, even when the stimulus onset asynchrony (SOA) is manipulated between 50 ms and 1000 milliseconds. This manipulation, which explores the effects of the psychological refractory period (PRP), shows how task coordination is influenced by the overlapping of tasks (see more on the effect of the PRP, Pashler, 1994).

It is important to note that coordination of multiple tasks is not simply passive but active and influences performance in the overall task organization. Several studies support this active nature of coordination. For example, de Jong's research on the role of preparation in overlapping task performance (de Jong, 1995) demonstrates that the active engagement of cognitive resources is necessary for effective coordination. Similarly, the work from Sigman and Dehaene (2008) on the brain mechanisms underlying serial processing suggests that the active management of cognitive resources is crucial for coordinating different task components. The active nature of coordination also directly impacts the overall organization of tasks. Kübler and colleagues' research (2022) on the organization of task order and task-specific control highlights how coordination influences the way tasks are structured and executed. Additionally, Hirsch et al. (2021) provided evidence in support of a hierarchical, multi-component model of cognitive control, which suggests that coordination plays a central role in the hierarchical organization of task-related processes. Thus, coordination's active and influential nature has important implications for task performance. Effective coordination allows individuals to efficiently manage the cognitive resources required for different task components, leading to improved overall performance. Conversely, breakdowns or deficits in coordination can result in suboptimal task organization and decreased performance.

The micro and macro level of multitasking

The concept of multitasking, as introduced earlier, can be further elucidated by examining it along a continuum proposed by Salvucci et al. (2009). This continuum delineates multitasking from sequential tasks spanning minutes or hours to concurrent tasks occurring within milliseconds or seconds.

Sequential multitasking, as exemplified by the cooking and breakfast task studied by Craik and Bialystok (2006), involves a series of tasks performed in succession, such as preparing a virtual breakfast and setting a table. This sequential nature allows for the completion of one task before transitioning to the next, enabling individuals to focus on and devote cognitive resources to each task individually. The sequential nature of multitasking tasks facilitates the use of cognitive strategies, such as task switching and task prioritization. Individuals can allocate attention and resources to one task at a time, allowing for more deliberate and controlled cognitive processing. This sequential approach can be beneficial in complex or cognitively demanding tasks, as it reduces the risk of interference and cognitive overload as supported by research on task switching, which has examined the cognitive mechanisms and processes involved in transitioning between tasks (Monsell, 2003; Rubinstein et al., 2001). These studies highlight the role of executive control in managing cognitive processes during task switching (Kiesel et al., 2010) within seconds.

In contrast, concurrent multitasking - as in dual tasking - involves the simultaneous management of multiple tasks within a compressed timeframe, often within milliseconds or seconds. This temporal overlap requires individuals to rapidly switch between tasks, coordinate cognitive resources, and maintain task-relevant information in working memory. Concurrent multitasking poses significant cognitive challenges, as individuals must navigate the interference and competition for limited cognitive resources. Thus, the distinction between sequential and concurrent multitasking is not always clear-cut because as well as task switching and dual tasking can occur within a few seconds.

As mentioned in the introduction, perhaps categorizing research on multitasking into macro and micro levels would provide further insights. The macro level encompasses application-oriented studies conducted in various settings, from controlled laboratory experiments to real-world field studies, aligning with the multitasking continuum. In contrast, the micro level focuses on laboratory-based investigations, such as dual-task studies examining task-switching dynamics. A precise definition is essential to establish a comprehensive understanding of multitasking at both macro and micro levels. Drawing from Oswald et al. (2007), multitasking involves (a) managing multiple tasks simultaneously, (b) intentionally transitioning between tasks, and (c) swiftly executing individual tasks within compressed timeframes (see also Redick et al., 2016). This definition underscores the complexity and dynamic nature of multitasking processes.

Macro level of multitasking

At the macro level, multitasking tasks outside the laboratory are often used to measure general multitasking ability. These tasks provide a practical and applied approach to assessing individuals' capacity to handle complex and dynamic multitasking scenarios. For instance, the ATC-lab$^{\text{Advanced}}$ (Fothergill et al., 2009) offers a simulated environment that mirrors the challenges faced by air traffic controllers, requiring participants to manage multiple aircraft movements simultaneously. Similarly, the Control Tower task (Redick et al., 2013) introduces distractions akin to real-world scenarios, where individuals must maintain focus on a primary task amidst competing demands. In military contexts, multitasking test batteries like MATB-II (Santiago-Espada et al., 2011) and SynWin (Elsmore, 1994; Hambrick et al., 2010) play a crucial role in evaluating the multitasking capabilities of potential pilots and air traffic controllers. These tasks encompass various sub-tasks that collectively assess an individual's ability to manage multiple concurrent activities efficiently. I will use the MATB-II as an example to delve into its details.

The MATB-II presents participants with a diverse set of tasks, each designed to challenge different aspects of multitasking proficiency. The system monitoring task requires individuals to respond promptly to changing signals, testing their vigilance and ability to prioritize information. In contrast, the tracking task involves controlling an aircraft using a joystick, demanding precise hand-eye coordination and spatial awareness. The communication task within MATB-II necessitates tuning a radio to specific frequencies upon hearing one's call sign, assessing participants' ability to switch attention between tasks seamlessly. Lastly, the resource management task involves maintaining levels in two tanks while managing potential pump failures or restarts unexpectedly, highlighting the importance of adaptive decision-making under pressure. The overall performance across all tasks is evaluated, and a general multitasking score is computed. This score allows us to predict performance in roles such as a pilot or air traffic controller (Hambrick et al., 2010; Redick et al., 2016). Lebiere et al. (2001), for example, simplified an air traffic control task and were able to make predictions about performance. However, scenarios with multiple tasks are challenging to model and, thus, to predict. Wickens (2002, 2008) also attempts to make predictions about the interference between the tasks and the workload with his multiple resource model, but it is primarily limited to dual tasks (Dixon et al., 2003).

While macro-level studies provide valuable insights into the predictive validity of multitasking performance measures in applied settings, they may not capture the intricacies of cognitive processes involved in multitasking at a granular level. This limitation underscores the significance of micro-level research, which delves into the underlying mechanisms of multitasking through controlled laboratory experiments and detailed cognitive analyses. Micro-level studies focusing on single and dual tasks offer a more nuanced understanding of how individuals allocate attention, switch between tasks, and manage cognitive resources during multitasking activities (Kiesel et al., 2010; Koch et al., 2018; Strobach, 2019, 2023). By examining these fundamental cognitive processes, researchers can uncover key factors influencing multitasking performance and develop targeted interventions to enhance multitasking abilities in various domains.

Micro level of multitasking

Multitasking at the micro level usually consists of two tasks (Kiesel et al., 2010, 2022; Koch et al., 2018; Pashler, 1994). These dual tasks can be divided into different paradigms: simultaneous multitasking with discrete tasks (Fischer & Janczyk, 2022), continuous tasks (Johannsen et al., 2022), or sequential multitasking with task switching (Koch & Kiesel, 2022) and task interruption (Hirsch et al., 2022). Different models explain the effects observed in each dual-task paradigm. While each model offers unique predictions, none comprehensively accounts for all observations. As discussed earlier, these models primarily focus on dual tasks and provide theoretical insights into multitasking with two tasks. However, none have extensively explored the impact of managing multiple tasks (more than two) simultaneously (Kiesel et al., 2022; Koch et al., 2018). Further research is needed to investigate the complexities and cognitive mechanisms involved in handling multiple concurrent tasks to enhance our understanding of multitasking beyond dual-task scenarios.

Structural models. A well-known and long-standing model in the field of multitasking is the response selection bottleneck model, initially proposed by Welford (1952) and further developed by Pashler and Christian (1994). This model posits that when two tasks are required, regardless of their modality, a bottleneck occurs in the response selection process, leading to sequential task execution. According to this model, the performance in the first task remains relatively stable, irrespective of temporal overlap between tasks. However, it is suggested that the performance in the second task is significantly affected by the degree of temporal alignment between tasks. Increased temporal overlap, indicated by a shorter Stimulus Onset Asynchrony (SOA) between stimuli, results in slower responses and higher error rates in the second task (for further discussions on the psychological refractory period, see Meyer & Kieras, 1997a; Pashler & Christian, 1994).

If we were to apply this model to a triple-task scenario, it would predict that response times in task 2 would be slower than in task 1, and response times in task 3 would be slower than in task 2. Consequently, the overall response time for the triple task would be significantly slower than that for a single task (refer to Figure 1(A)). However, empirical findings suggest that such a simplistic prediction may not accurately capture the complexities of multitasking. Wickens and Liu (1988) proposed a different perspective, suggesting that multiple resources are available and bottlenecks only occur when the same resource is utilized concurrently. In such cases, individuals can respond to two tasks simultaneously.

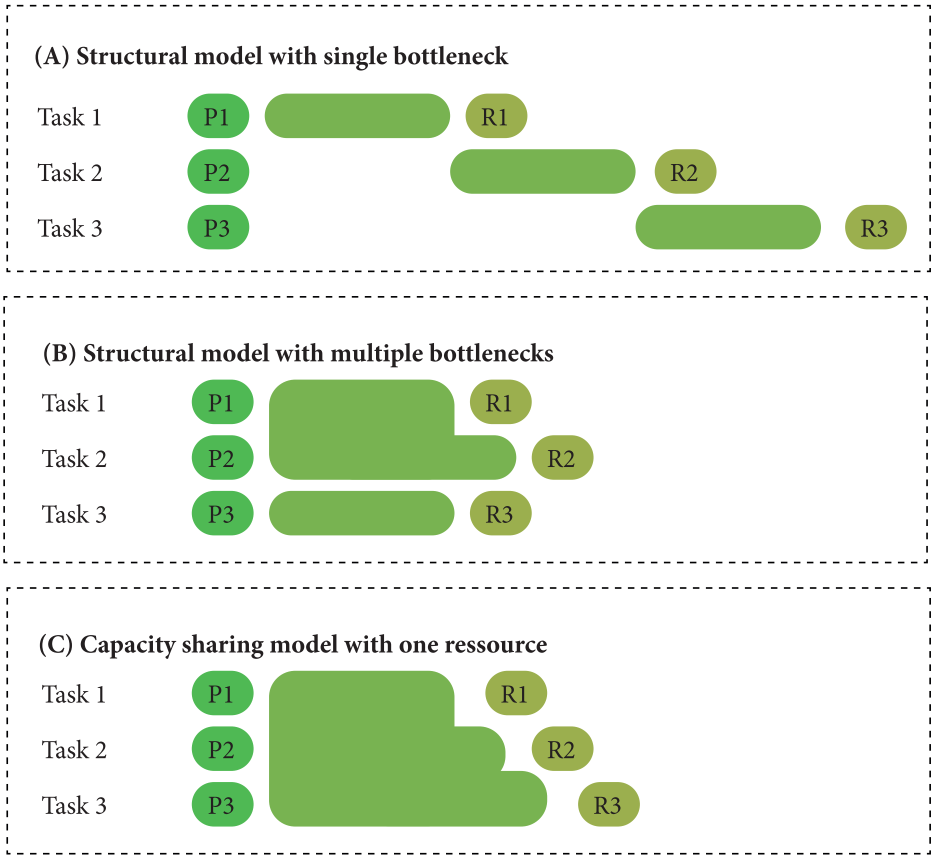
Models such as ACT-R (Anderson et al., 2005) and the EPIC framework (Meyer & Kieras, 1997a, 1997b) share a common approach in which tasks are executed on separate processing threads, allowing for concurrent operation. Although these models vary in their specific assumptions and processes, they both suggest that it is possible for three or more tasks to run in parallel with performance levels comparable to that of a single task (see Figure 1(B)). However, to the best of my knowledge, these assumptions have not been empirically tested with more than two tasks, making these conclusions speculative and based solely on theoretical grounds. This situation highlights the intricate nature of multitasking dynamics and emphasizes the need for more sophisticated models to accurately represent the capabilities for parallel processing in multitasking scenarios with more than two tasks.

Capacity sharing models. Pure resource models (Navon & Miller, 2002; Tombu & Jolicoeur, 2004; Tombu & Jolicøeur, 2003) offer a different perspective on multitasking bottlenecks. These models do not attribute bottlenecks to specific processing areas like response selection but rather emphasize the inherent limitation of human cognitive resources that must be allocated efficiently. In the central capacity sharing model proposed by Tombu and Jolicøeur (2003), the term "resources" refers to the cognitive capacity or mental resources that individuals possess and allocate to perform various tasks. These resources include attentional resources, working memory capacity, processing speed, decision-making abilities, and other cognitive functions necessary for task performance. According to this model, these resources are limited and must be flexibly distributed among the concurrent tasks during multitasking. In this framework, parallel processing is feasible and contingent upon resource allocation. The ability to process two or more tasks concurrently with the same level of performance as a single task hinges on the availability and optimal utilization of these cognitive resources (see also Norman & Bobrow, 1975). When tasks compete for the same limited resources, performance on all tasks suffers. However, when the tasks can be executed using distinct resources, parallel processing becomes possible, and the performance on each task can be maintained at a level comparable to single-task conditions. In scenarios where resources are optimally allocated, it is conceivable that three tasks could be completed more rapidly than in comparison to the assumption of bottlenecks according to structural models (see Figure 1(C)). However, making precise predictions in such resource-based models is challenging due to the ambiguity surrounding the precise definition and characterization of the cognitive resources involved in multitasking (for an in-depth discussion on the limitations of current models, see Musslick & Cohen, 2021). This highlights the evolving nature of our understanding of multitasking dynamics and the ongoing quest to elucidate the intricate interplay between cognitive resources and task performance in complex multitasking scenarios.

Summary of macro and micro level. The exploration of multitasking across both macro and micro levels reveals a significant divide in the research landscape. At the macro level, studies tend to focus on practical, real-world applications of multitasking, employing complex tasks that mimic the challenges encountered in everyday scenarios or specific professional settings. These studies aim to assess individuals' ability to manage multiple tasks simultaneously, often in dynamic and unpredictable environments. The use of tasks with better ecological validity, such

Figure 1

Three-task modeling of dual-task models



Note. A schematic illustration of the performance dynamics of three tasks under different theoretical dual-task frameworks. Panel (A) depicts the scenario where a central bottleneck dictates task execution independent of the tasks, meaning after perception (P1, P2, and P3) each task must wait its turn, resulting in the longest response times (R1, R2, and R3 which are responses) (Pashler & Christian, 1994). Panel (B) illustrates a model where multiple bottlenecks or sequential processing may occur. In this model, task 1 and task 2 are processed in such a way that the performance of task 2 is hindered by task 1, likely due to competition for the same cognitive resources. Meanwhile, task 3 is able to operate at full capacity, presumably because it utilizes different resources that are not in contention with tasks 1 and 2 (Anderson et al., 2004; Meyer & Kieras, 1997a; Wickens & Liu, 1988). In contrast, Panel (C) envisions a system without structural bottlenecks. Here, a shared resource allows for more flexible task performance independent of tasks, potentially improving overall efficiency compared to a single bottleneck system (Tombu & Jolicøeur, 2003).

as those found in air traffic control simulations or military multitasking test batteries, provides insights into how individuals navigate the demands of real-world multitasking, balancing attention and cognitive resources across various tasks.

Conversely, the micro level delves into the fundamental cognitive processes underlying multitasking through controlled laboratory experiments. These studies often employ dual-task paradigms to isolate and examine the mechanisms of attention allocation, task switching, and cognitive resource management. By focusing on simpler tasks and controlled conditions, micro-level research seeks to uncover the basic principles that govern multitasking performance, offering a more granular understanding of how individuals process multiple tasks concurrently. Therefore, I will take a closer look at dual tasks, especially dual-task training and transfer.

Dual-task training and transfer

One of the most cited (over 755 times according to Google Scholar) and discussed (e.g. Anderson et al., 2005; Hazeltine et al., 2002; Maquestiaux et al., 2008; Tombu & Jolicoeur, 2004) dual-task training studies is that of Schumacher et al. (2001). In several experiments, participants trained both an auditory-vocal and a visual-manual task. While differences in performance between single and dual tasks could still be observed in their study in the first session, no more differences were found in session 5. In both tasks, a performance improvement was observed, which can be attributed to the fact that the task itself is processed more efficiently. This can be achieved, for example, by shortening the response selection (Schubert et al., 2008) or other processing stages (Dux et al., 2009; Strobach et al., 2013), bypassing the central bottleneck (Maquestiaux et al., 2008, 2018; Ruthruff et al., 2001), or automatization (Ruthruff et al., 2006; Schneider & Shiffrin, 1977); see also the review from Strobach and Schubert (2017). However, the improvement in the dual task is not due to the improvement in both tasks but mainly in the second task, namely the auditory task (Strobach, Frensch, et al., 2012; Strobach, Liepelt, et al., 2012; Tombu & Jolicoeur, 2004). The crucial factor is, therefore, task coordination, which is improved by dual-task training but not with single-task training (Strobach et al., 2014). This approach is pursued by the Efficient Task Instantiation (ETI) model. The ETI model, proposed by Strobach et al. (2014) (Schubert & Strobach, 2018), plays a pivotal role in explaining the benefits observed from dual-task training. According to this model, the improvement in dual-task performance is attributed to a more efficient transition between tasks. This efficiency is achieved through the effective loading of relevant task information into working memory at the onset of a dual-task trial. The ETI model posits that the task sets for both tasks, including crucial stimulus-response mapping rules, are simultaneously but separately represented in working memory. This distinct yet concurrent maintenance of task sets ensures that each task's requirements are readily accessible, facilitating a quicker and more seamless transition between tasks. In a recent review, Schubert et al. (2024) discussed that working memory must play a pivotal role in dual-task practice, and task instantiation at the beginning of a dual-task trial is elementary for the dual-task practice advantage. They formulated three critical predictions to test the assumptions of the ETI model: (1) individuals can acquire dual-task coordination skills through practice and successfully transfer those skills to other situations, (2) the complexity and difficulty of the individual tasks being performed simultaneously affect the development and execution of dual-task coordination skills, and (3) age-related reductions in working memory capacity influence the ability to optimize and improve dual-task performance through practice. It is important to note that dual-task practice does not imply the tasks are merged into a single set (a concept referred to as task integration by Ruthruff et al. (2001, 2006)); rather, it means each task set is distinctly but concurrently maintained in working memory. Schubert et al. (2024) note, however, that the working memory hypothesis is not a stand-alone answer to the models but rather an extension, e.g., to the EPIC Framework (Meyer & Kieras, 1997a, 1997b). Furthermore, it extends our understanding of task coordination improvement effect on dual tasks. Karbach and Strobach (2022, p. 324) explain the optimized task coordination of the dual task 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 & 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)."

Thus, the enhancement of efficient task instantiation and the coordination of tasks through training contributes to improved performance in dual tasks. The improvement appears to be partly task-independent.

As depicted in Figure 1(B), even if there are no results yet, this training can also significantly enhance the processing of three or more tasks. Initially, coordinating three tasks proves more challenging than dual tasks due to the increased number of tasks and associated rules. However, with training, the performance improvement for a triple task should surpass that of a dual task. Moreover, by training both single and dual tasks, participants could be trained to such an extent that even easily handled tasks could be processed better. Although Schubert and Strobach (2018) assume that it will be difficult to keep all mappings in the working memory if there are more than 6 - 10 stimulus-response mappings, however, rules (Dreisbach & Wenke, 2011; Mayr & Kliegl, 2000) and the chunking mechanisms in human learning (Cowan, 2001; Gobet et al., 2001) as stimulus-response mappings (Duncan, 1979) also play a role in training multiple tasks (see also Schubert et al., 2024).

Liepelt, Strobach, et al. (2011) were able to show that training of stimulus-response mappings (tasks) can improve performance on other, untrained mappings (tasks) (Bherer et al., 2008; Schubert et al., 2017; Strobach, Frensch, et al., 2012; Strobach et al., 2014). Schubert et al. (2024) suggested that the skills developed through dual-task training, particularly the efficient instantiation of task sets in working memory, can be transferred to other multitasking scenarios. This transferability is crucial for the practical application of dual-task training, as it implies that improvements in task coordination and cognitive flexibility gained through training can enhance performance in a wide range of multitasking environments.

However, the statements from the previous dual-task studies are only limited to near transfer effects, i.e., that the transfer could only be proven for very similar stimulus-response mappings (Schubert et al., 2017). This means that the skills acquired through dual-task training may not generalize to tasks that are significantly different from the trained tasks. The transfer of skills is more likely to occur when the untrained tasks share similar characteristics, such as stimulus modality, response modality, or cognitive processes involved.

Garner and Dux (2023) also come to this conclusion in their perspective paper on knowledge generalization in the context of multitasking. They argue that the specific characteristics of the trained tasks may limit the generalization of knowledge and skills acquired through multitasking practice. The authors suggest that the transfer of skills to novel tasks may be hindered by the cognitive costs associated with adapting the learned strategies to new task demands. This implies that the benefits of dual-task training may be more pronounced when the transfer tasks are closely related to the trained tasks, and the generalization of skills to dissimilar tasks may be more challenging.

Aim of the dissertation

In the realm of current research, there are two primary branches of focus: one that examines the macro-level effects of applications without delving into the underlying causes and another that scrutinizes the micro level causes, developing predictive models within a dual-task framework. My research endeavors to bridge these approaches by extending the micro level analysis into the realm of triple tasks, thereby pushing the boundaries of existing models and assumptions.

The core of my dissertation introduces a novel approach by integrating well-defined tasks from the micro level — tasks that can be accurately predicted individually with different models — with activities from the macro level, breaking them down to a more granular level. An example of this integration is the act of driving a car, which engages the driver in processing visual and auditory information and requires motor actions in response to these inputs. The driver must constantly perceive and interpret visual cues from the road, traffic signs, and other vehicles while listening for relevant sounds such as horns or sirens. Based on this sensory information, the driver must execute appropriate motor actions like steering, accelerating, or braking. Verbal communication with passengers adds another layer of sensory input and potential response. This example serves as a simplified illustration of the complex interplay of sensory processing and motor outputs that my research aims to explore.

To illuminate this complexity in the lab, I have designed a study that employs three two-choice component tasks, each chosen for their maximal compatibility to facilitate learning and performance in a triple-task scenario. These tasks include a visual-manual task (or location-hand task), where participants respond with their dominant hand to a visual stimulus in a spatially compatible manner; an auditory-vocal task, where responses to pitch are made vocally (pitch-voice task); and a visual-pedal task, which introduces a second visual input and utilizes the feet as an additional response modality (color-feet task). The tasks are thus selected in such a way that their features are as appropriate as possible (see *intra-coordinative complexity* in section *What makes a task "complex"*). One could argue that there are overlaps between the various stimuli and responses in the input and output systems. For instance, locality and color are perceived through the visual system, and all stimuli are responded to using the motor system, as hands, feet, and voice require musculature to produce a signal. However, results from Treisman and Gelade (1980) showed that it is indeed possible to perceive multiple features in the visual search field when they are in a $<$ 1-degree visual angle. In cognitive research, the output system is also separated by (motor) modality. There seem to be different processors, as demonstrated by Schumacher et al.'s (2001) study, in which voice and hands reacted differently depending on training status, and Pashler and Christian's (1994) study, which revealed different bottlenecks between hands and feet. Furthermore, the combination of these three tasks exhibits an increased complexity and need for inter-coordination. Especially for hand-foot coordination, difficulties may arise depending on the specific combination of tasks (see therefore Stroop, 1935). By carefully balancing these tasks, I aim to counteract these effects. Additionally, each study was designed to ensure that participants had sufficient practice with the tasks. This was done to ensure, as much as possible, that every participant understood the tasks and could pursue the correct and consistent goal (as discussed in sections *What is a task?* and *What makes a task "complex"*).

Given the absence of published studies on the dynamics of triple tasks and the extent to which existing models are transferable to them, my initial study is designed to explore these aspects, thereby contributing to a deeper understanding of task complexity and human performance. This research extends previous studies at the micro level to include triple tasks and integrates insights from macro-level analyses, offering a comprehensive view of task performance and its underlying mechanisms.

Contribution 1

Expanding dual-task research by a triple-task

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Research Article

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Expanding dual-task research by a triple-task

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Abstract: Multitasking research in the laboratory is dominated by extremely simplistic dual-task paradigms. Although dual-tasks allow for some variations, they do not compare well to more complex everyday task settings. This study expands a classical dual-task paradigm by adding a third task. The dual-tasks and the triple-task always consisted of the same three single tasks. The aim was to investigate the effects of the combinations of the three single-tasks and in which manner response times and costs increased. Stimulus-response pairings were varied either once within participants (E1) or between participants (E2). Our results showed that the increase in response time from dual-tasks to triple-tasks was only 43% of the increase from single-tasks to dual-tasks suggesting a non-linear cost of adding tasks. Moreover, response times in each subtask were higher in triple-task situations compared to single-task or dual-task situations. This is in contrast to classical dual-tasks, in which typically only one of the two responses is delayed. Cognitively, for costs in triple-tasks, unlike in dual-tasks, task coordination seems to play a larger role compared to the classically suggested relationships between stimulus and response in terms of their modality- and ideomotor-compatibility which we will discuss. Overall, the study demonstrates that current multitasking research is limited in its generalizability by focusing only on dual-tasks and would benefit from research with more complex task settings.

Keywords: dual-task; triple-task; task coordination; multitasking.

1 Introduction

Multitasking can be found in different areas of everyday life. When driving a car, several tasks have to be performed simultaneously, such as navigating, steering, braking, and keeping an eye on the environment. Problems may arise if the driver, for example, is also taking a phone call while driving, leading to longer response times, or issues completing one of the two tasks successfully (Nijboer et al., 2016; Strayer & Johnston, 2001). However, under which circumstances can we talk about *multitasking*? Is driving a car really a form of multitasking, or have several tasks merged into one big task with several subtasks?

The term *task* refers to a cognitive or behavioral goal, which is given by instructions (Monsell, 1996). Instructions provide a clear specification of how a task must be processed. In addition, people must also be willing to accept these instructions as their task (see, Hackman, 1969; Künzell et al., 2018 for a discussion on task definition). Classical studies on multitasking using clearly defined and isolated stimuli, such as sounds or visually presented forms. This allows manipulating the time between the presentation of the first and second stimulus on a millisecond level. A common way to investigate human multitasking with such simple tasks is the dual-task paradigm (see, e.g., Koch et al., 2018, for a review). Studies based on the dual-task paradigm investigated the performance of participants in

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a dual-task in relation to their performance in single-tasks (Pashler & Sutherland, 1998). In a dual-task, two stimuli are to be processed simultaneously, which often results in poorer performance (response time) and higher error rates (Kahneman, 1973; Koch et al., 2018; Norman & Bobrow, 1975; Pashler, 1994; Wickens, 2008). The combination of two simple tasks into a dual-task is still the dominant paradigm in multitasking research and reflects the lowest level of multitasking complexity. Multitasking research based on dual-tasking started with Welford (1952), who examined the effect of the psychological refractory period (PRP) with two stimuli, and since then several research aspects such as task performance limiting factors (Norman & Bobrow, 1975), different paradigms (Monsell, 2003; Pashler, 1984, 1994), modalities (Pashler, 1990; Schumacher et al., 2001), automatization (Maquestiaux et al., 2018; Strobach & Schubert, 2017b), processing order (Strobach et al., 2018), attention control (Hirst et al., 1980; Kramer et al., 1995), inhibition (Koch et al., 2010), long-term training effects (Bherer et al., 2005; Liepelt, Fischer, et al., 2011; Schumacher et al., 2001; Strobach & Schubert, 2017a), and transfer effects (Bherer et al., 2008; Liepelt, Strobach, et al., 2011; Strobach et al., 2012) have been investigated. Though, increasing the task's complexity by adding one or even more additional tasks was not systematically studied yet.

Multitasking can be classified in both a time and an application dimension. The time dimension distinguishes between concurrent and sequential multitasking while the application dimension distinguishes between the laboratory and the real world (Salvucci & Taatgen, 2010). Aforementioned dual-tasks are concurrent and take place in laboratory settings, whereas (driving) simulators (Nijboer et al., 2016; Watson & Strayer, 2010; Wechsler et al., 2018) or other complex tasks (Gutzwiller et al., 2019; Santiago-Espada et al., 2011) are closer to real-world tasks. In this area, there are also multitasking tasks for purely diagnostic aspects (Schuhfried, 1991) or studies that combine real-world aspects (such as a walking task) with laboratory tasks (Laessoe et al., 2008). There are only selected studies that extended the classical dual-task paradigm by adding a simple third task to form a basic triple-task paradigm. Recently, Konishi and colleagues (2021) have also extended a dual-task (Konishi et al., 2020) to a triple-task (Konishi et al., 2021) to determine whether participants have the ability to track their performance based on self-evaluation (metacognitive sensitivity). They used an adaption of the MATB (Santiago-Espada et al., 2011), but at the end of each trial, participants had to self-evaluate their performance. Konishi et al. (2021) could observe an increase in multitasking costs and that the number of tasks (dual-task vs. triple-tasks) had a great impact on further cognitive processes, such as metacognition. Consequently, adding a third task can grant valuable insight into how interference change when demands increase and can give a better approximation of how handling multiple concurrent tasks might be realized in complex every-day situations.

The current research in the field of dual-/ multi-tasking does not allow straightforward hypotheses about the effects of a third task on dual-task performance. Theories, such as the resource theory of Wickens (see also Tombu & Jolicœur, 2003; Wickens, 1981), Pashler's (1984, 1990, 1994) response selection bottleneck (RSB), or the executive-process interactive control (EPIC) architecture of Meyer and Kieras (1997b, 1997a) are based exclusively on studies with two tasks. Even in dual-tasks, those theories fall short in one way or the other. The RSB model does not account for why some dual-tasks can be completed simultaneously without costs while others don't (Schumacher et al., 2001). This shortcoming was partly resolved in resource models (Tombu & Jolicœur, 2003), but these models also leave the exact processes open. Exact modeling of task execution by a program specifying variables, operators, sequences, and loops is not possible. For example, Hommel (2020) also criticizes their "lack of mechanistic detail". For instance, it is not possible to explain why some subtasks are prioritized, or why different interferences occur in different modules (effector systems). The EPIC architecture also fails to explain the latter (Hoffmann et al., 2019). The Theory of Event Coding (TEC) advocated by Hommel (2019; Hommel et al., 2001) ventures on an extended approach, even though it has not yet found any concrete application in multitasking research (Hommel, 2020). According to TEC, a single, common representation medium for perceived events and the intended reaction or action forms the core structure of the functional architecture for perception and reaction planning. Its key assumption is that stimulus representations and action intentions are not differently coded, rather they are part of a common code, a common representational medium. If such a feature code (e.g., a location) is already bound in Task 1 but is also needed in Task 2, it needs to be unbound, which incurs costs in the form of time and errors. Koch (2009) showed that such overlapping response codes resulted in higher response times, an effect described as "strong crosstalk between the two tasks".

Thus, not only do the stimuli themselves have an impact on multi-tasking costs, but also (the interaction of) their response modalities (Huestegge & Hazeltine, 2011). The bindings between stimulus and response can, in their modality or ideomotor feature, be compatible or incompatible (Stephan et al., 2021; Stephan & Koch, 2010). For example, a task is considered modality-compatible if a visual stimulus is responded to with a manual or a pedal effector. Modality incompatibility occurs when the visual stimulus must be responded to with a vocal effector. The characteristics of the stimulus influence the compatibility of the stimulus and response bindings. If the visual stimulus appears on the left side and is responded to with the right hand the binding is considered ideomotor incompatible (for a review see, Shin et al., 2010). Hazeltine et al. (2006; see also Hazeltine & Ruthruff, 2006) showed that the dual-task costs were more than twice as high in tasks with modality-compatibility than incompatibility. Göthe et al. (2016) broke this down even further: They did not only examine the modality-compatibility of stimulus and response (modality pairing) but also whether the features within a task were compatible (ideomotor compatibility), i.e. whether a location stimulus appearing on the left side of the screen must also be responded to with a left button (modality and ideomotor bindings are compatible). Essentially, dual-tasks were used to induce high versus low interference conditions by using two kinds of stimulus-response (S-R) pairings (Göthe et al., 2016; Hazeltine et al., 2006; Tombu & Jolicoeur, 2004). The high interference condition is realized by two visual-manual (S-R) pairing tasks, the low interference condition is realized by a combination of a visual-manual and auditory-vocal task.

If typical dual-tasks are extended by adding another task, several considerations stand to reason. As previously mentioned, it is difficult to construct three tasks that can be assigned to three completely independent S-R-pairings. For response modalities, in most classic dual-task studies investigating S-R pairings, hand and voice are used. They usually constitute the S-R pairings visual-manual and auditory-verbal, where the visual modality is defined as a location task (left or right) and the auditory modality as a pitch task (high or low). The response modalities foot (Hoffmann et al., 2019; Liepelt, Fischer, et al., 2011; Naefgen et al., 2017; Pashler & Christian, 1994; Sangals et al., 2007; Stephan et al., 2021) and eye movements (Hoffmann et al., 2019; Pieczykolan & Huestegge, 2014; Stephan et al., 2013), in contrast, received little attention. Even though previous results have shown that oculomotor responses (eye movements as response modality) are a good complement to previously employed response modalities, pedal tasks separate input and output modality more clearly even if manual and pedal tasks supposedly cannot be processed in parallel (Pashler & Christian, 1994). This was also suggested by the results of Hoffmann et al. (2019). In task switching, Stephan et al. (2021) were able to show that pedal responses produced the equivalent effects of manual responses. Dual-tasks with both response modalities demonstrated very high dual-task or switching costs. Furthermore, Hoffmann et al. (2019) showed that there is a task prioritization in response times of oculomotor < pedal < vocal < manual (we refer to this as response order 1). However, this prioritization is not in line with all dual-task studies (see Hazeltine et al., 2002; Schumacher et al., 2001), but the prioritization of (sub)task was observed in some studies (e.g. Hazeltine et al., 2006; Huestegge & Koch, 2013). Based on other studies using pedal responses (e.g., Liepelt, Fischer, et al., 2011), a prioritization of oculomotor < manual < pedal < vocal would also be plausible (response order 2). To be comparable to well-known dual-tasks studies, in the present study, we used similar stimulus-response mappings as Schumacher et al. (2001; see also Hazeltine et al., 2002; Hoffmann et al., 2019; Pashler & Christian, 1994). Stimuli remained as simple as possible with a location (left or right location), pitch (high or low pitch), and color task (green or turquoise color). The color discrimination task was comparable to the location task (Pisella et al., 1998) and should induce little interference with the location and pitch task due to the use of other ideomotor features (Shin et al., 2010). Thus, all three tasks were comparable to each other and similarly difficult. Consequently, the resulting triple-task was made up of a visual-manual, a visual-pedal, and an auditory-vocal task (with response modalities hand, foot, and voice).

In summary, the following assumptions about this triple-task can be made based on previous findings: First, we assume a clear prioritization of the subtasks, which will be either pedal < vocal < manual (Hoffmann et al., 2019, response order 1) or manual < pedal < vocal (Hazeltine et al., 2002; Liepelt, Fischer, et al., 2011, response order 2), which will be visible in the modality-specific response times. As in response order 2, we assume a high prioritization of the manual and pedal task, since both are important and elementary response modalities in everyday life. Second, we assume that there is some limited interference between the two visual tasks due to (weak) crosstalk (Koch, 2009) or due to a bottleneck in the visual system in terms of the dual-task framework (Tombu & Jolicøeur, 2003; Wickens, 1981). This could be circumvented by participants prioritizing tasks in response order 1 (pedal < voice < manual). By procedurally separating the manual and pedal task by the voice task, a bottleneck could be bypassed which in turn could show up in low costs for participants with response order 1. Third, since sub-task response times are higher for dual-tasks than comparable single-tasks (Schumacher et al., 2001, e.g.), we assume further increases in response times for triple-tasks. As an exploratory analysis, it will be interesting to see whether a linear, or non-linear increase of response time can be observed from single-task to dual-task to triple-task. The increase would be linear if the increase in cognitive demands from a single to the dual-task is comparable to the increase in cognitive demands from the dual-task to the triple-task and the increase would be non-linear accelerating, respectively decelerating, if the increase in cognitive demands from the dual-task to the triple-task is higher, respectively, lower compared to the increase from the single to the dual-task.

For our triple-task paradigm, as with the dual-task paradigm, all three stimuli were shown simultaneously. We also instructed equal prioritization of all three tasks (Schumacher et al., 2001; Stelzel et al., 2006). We focused on the comparison of single- and triple-tasks in the first experiment and on the comparison of single-, dual-, and triple-tasks in the second experiment. All tasks were presented in a mixed-block design to prevent task preparation (see, Kiesel et al., 2010 for a review).

2 Experiment 1

To directly compare the performance in the triple-task with the performance in each of the three single tasks, we exclusively used single-tasks and triple-tasks and we tested different S-R pairings for the two visual tasks. We switched response modality only in the visual task, as there have been very few comparable studies on the foot response modality, in contrast to the response modalities hand and voice. Thus, participants performed the tasks in a within subject design either with the S-R pairing location-hand and color-foot, or location-foot and color-hand, and each task pair was combined with pitch-voice.

2.1 Methods

2.1.1 Participants

19 students (9 females and 10 males, *M* = 23.32, *SD* = 2.60) took part in this experiment. All participants had normal or corrected-to-normal vision and no hearing impairments. They provided informed consent and were given course credit or ~9 € as compensation for their participation. Due to a technical equipment failure, four records were lost. Thus, 15 participants were included in the final analysis.

2.1.2 Setup

The experiment was programmed in MatLab® 2019a with the Psychtoolbox-3.013 (Brainard et al. 2016) on a PC running Linux OS® with Ubuntu 18.04 LTS. The study was conducted in noise-reduced medium-lit cabins. The visual stimuli were displayed on an EIZO® color monitor with a screen diagonal of 27 inches and a frame rate of 144 Hz at a resolution of 3840 × 2160 pixels. The BlackBox® toolkit response pad with a voice key feature was used to capture response time of the motor and the vocal responses. One visual task was completed with the index and middle finger of the dominant hand via two adjacent keys on the response pad. The other visual task was completed with both feet on the respective foot pedals. The Sennheiser® Model PC3 headset was used to record the participants' voice and reproduce the auditory stimuli.

2.1.3 Task

As an extension of the basic methodology of Schumacher et al. (2001; see also Hazeltine et al., 2002), participants performed three two-choice response time tasks: a visual-manual (color or location discrimination), a visual-pedal (location or color discrimination), and an auditory-vocal (pitch discrimination) task. Each task sequence was structured as follows: first, participants were presented a fixation screen for 500, 1000, or 1500 ms with a white square (3.7° side length) as a fixation object in the center of the screen. Second, the stimuli in the single-tasks were presented for 200 ms and the white fixation square stayed on the screen until the participant responded (see Fig. 1). In the location discrimination single-task, participants responded with their hand or feet, depending on the S-R pairing, to the location (and direction) of a white arrow (1.5° height) appearing randomly and equally distributed at the left or right side of the fixation square by pressing a button (left arrow with the index finger or left foot and right arrow with the middle finger or right foot). In the color single-task, participants responded with their hand or feet, depending on the S-R pairing, to the color that the fixation square (and the arrow shown if necessary) turned to. The color was either green (RGB: 0, 255, 0) or turquoise (RGB: 0, 255, 255). The participants responded with a button press (green square with the index finger or left foot and turquoise square with the middle finger or right foot). In the pitch single-task, participants responded vocally via the voice key to a heard sine wave tone at frequencies of either 350 or 1650 Hz by saying “TIEF” or “HOCH” (German for: “LOW”/ “HIGH”).

In the triple-task, participants had to respond to all three tasks simultaneously (tasks were presented with an SOA of 0 ms).

2.1.4 Design

Participants had to complete two S-R pairing conditions (color-foot, location-hand, and pitch-voice (CF|LH|PV) and location-foot, color-hand, and pitch-voice (LF|CH|PV)) in the same session in two distinct S-R orders (order A with first S-R pairing: CF|LH|PV and order B with first S-R pairing: LF|CH|PV, see Fig. 1). One S-R pairing condition consisted of three different uniform blocks and five mixed blocks. A uniform block comprised of 20 trials of only one type of single-task in the order location (LH or LF), color (CF or CH), and pitch (PV). A mixed block consisted of the three single-tasks and the triple-task with a total of 12 single-tasks and 40 triple-tasks in each block. The tasks were randomly distributed in each block. In total, in uniform blocks, the participants completed 120 single-task trials. In mixed blocks, they completed 120 single-task trials and 400 triple-task trials. Half of the participants started with S-R order A, followed by S-R order B, and the other half vice versa. Participants were instructed to perform all the tasks as quickly and accurately as possible. They were told not to respond in a particular order and to give equal priority to all tasks. In total, participants had to participate in three sessions on three consecutive days. On each day, they completed both S-R pairing conditions.

2.1.5 Analyses

Vocal responses were analyzed at the time the voice key was triggered using the R-Package “VoiceExperiment” (Nett, 2017). For unclear cases in the analysis, trials were listened to and manually classified. RStudio 3.5 (RStudio Team 2016) was used with the tidyverse package version 1.2.1 (Wickham 2017) for data preparation and creating figures and jamovi version 1.1 (jamovi project 2018) to calculate repeated measure ANOVAs and post hoc analyses. For the analyses of all effects, we included single-task and triple-task trials only from mixed blocks (uniform blocks were only used for training the S-R pairings). Only correct trials were included in the analyses. This means that in the triple-task all three tasks had to be responded correctly (error rate in single-tasks: 4.9 %, triple-task: 10.2 %). All trials with response times faster than 80 ms and slower than 4500 ms were removed (single-tasks: 0.9 %, triple-task: 2.9 %). If not stated otherwise, we calculated mean response times per participant and S-R order. Post hoc tests were conducted on the estimated marginal means with Welch’s *t*-test and we used the Welch-Satterthwaite equation for computing degrees of freedom.

2.2 Results

In the following analysis, we considered the effects of the single-tasks (ST) and the triple-task (TT) in mixed-blocks. For the analyses, the response times of single-tasks and the triple-task were calculated separately in repeated measures ANOVAs. The effects were examined by post hoc comparisons.

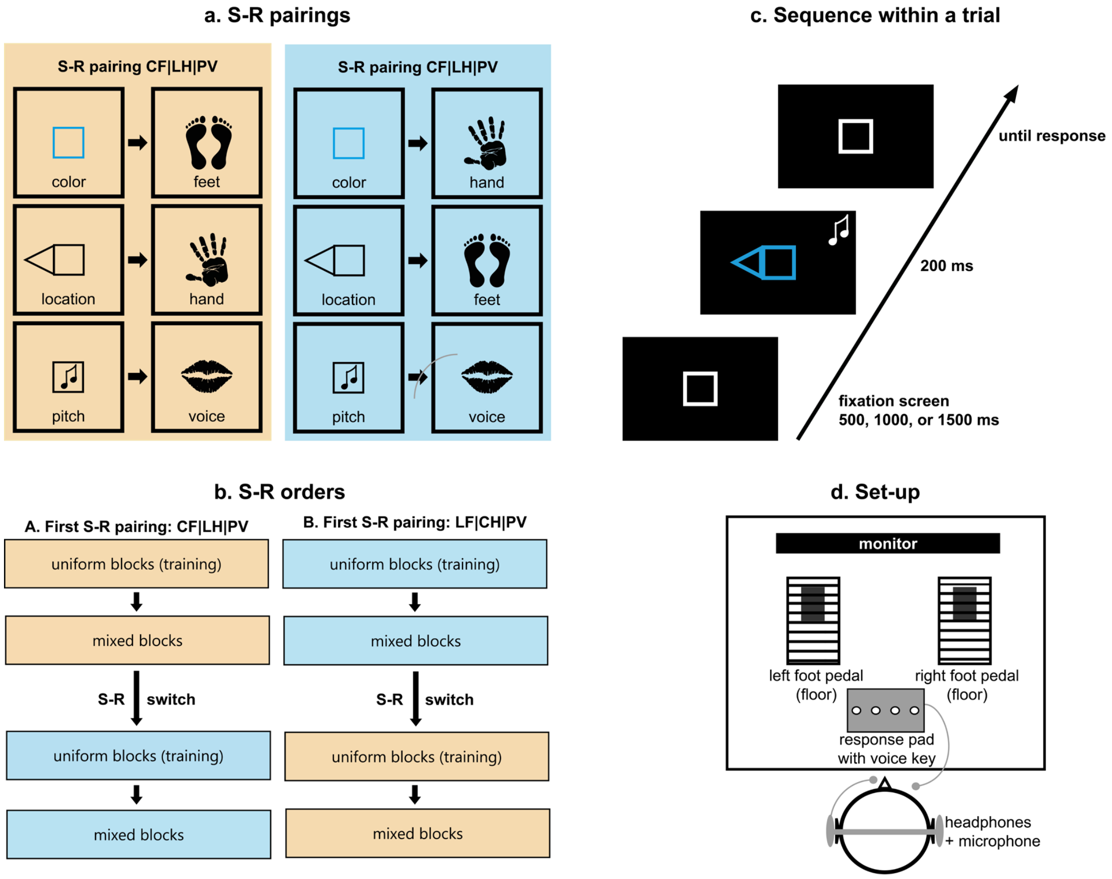

Figure 1: Schematic representation of the design and the tasks. a. shows both possible stimulus-response (S-R) pairings. In the S-R pairing CF|LH|PV, participants had to respond to the color (green or turquoise) of the fixation square with their feet, the location of the arrow (left or right) with their dominant hand, and to the pitch (low or high) with their voice. In the S-R pairing LF|CH|PV, the participants had to respond to the color with their hand, to the location of the arrow with their feet, and the pitch with their voice. b. shows both S-R orders which also represent the between-subject factor. In S-R order A, participants first had to perform the stimulus-response pairing (S-R pairing) color-foot, location-hand, and pitch-voice (CF|LH|PV) and then location-foot, color-hand, and pitch-voice (LF|CH|PV). In the S-R order B, the S-R pairings were reversed in order. In each S-R pairing, participants first practice each task separately in a uniform block. Mixed blocks consist of single-tasks and the triple-task. c shows the sequence of a triple-task trial. After the fixation screen, the stimuli appear for 200 ms. Until the response, the same screen as for the fixation screen is seen again. The note is visible only for illustration. d shows the set-up in the laboratory. Participants responded with their feet, dominant hand, and voice. The voice was timed with the voice key of the response pad and recorded with the microphone of the headphones.

2.2.1 Performance in single-tasks in mixed blocks

We analyzed single-tasks from mixed blocks to investigate how they are processed in the triple-task context. Single-tasks in uniform blocks were not analyzed in detail. They served only as a brief training to get used to the current S-R pairing. In general, the response times of single-tasks in mixed blocks increased considerably in comparison to single-tasks in uniform blocks.

A repeated-measures ANOVA was calculated for single-tasks in mixed-blocks with response modality (foot, hand, vs. voice) and S-R pairing (CF|LH|PV vs. LF|CH|PV) as a within-subject factor. The main effects for response modality, $F(2,28) = 2.99$, $p = .066$, $\eta^2_p = 0.176$, and S-R pairing, $F(1,14) = 1.44$, $p = .250$, $\eta^2_p = 0.093$, were not significant. The interaction of response modality and S-R pairing, $F(2,28) = 20.90$, $p < .001$, $\eta^2_p = 0.599$, was significant.

For the interaction response modality and S-R pairing we observed that response times depended on the stimuli (see Table 1. for descriptive values). In S-R pairing CF|LH|PV, location-hand (*M* = 733 ms) was faster than pitch-voice (*M* = 867 ms), *M* = -133 ms, *t*(53.8) = -2.67, *p* = .01, 95 % CI for *M* [-234 ms, -33 ms], and pitch-voice was faster than color-foot (*M* = 1052 ms), *M* = -185 ms, *t*(53.8) = -3.7, *p* < .001, 95 % CI for *M* [-286 ms, -85 ms]. In S-R pairing LF|CH|PV, location-foot (*M* = 849 ms) was faster than pitch-voice (*M* = 903 ms), *M* = -183 ms, *t*(53.8) = -3.65, *p* < .001, 95 % CI for *M* [-283 ms, -82 ms], and pitch-voice was faster than color-hand (*M* = 1032 ms), *M* = -129 ms, *t*(53.8) = -2.59, *p* = .012, 95 % CI for *M* [-230 ms, -29 ms].

Table 1: Response times and standard deviations in milliseconds for single-tasks and triple-task from mixed-task blocks and stimulus-response (S-R) pairings (color-foot, location-hand, and pitch-voice (CF|LH|PV) and location-foot, color-hand, and pitch-voice (LF|CH|PV)).

Task	S-R pairing	Foot		Hand		Voice	
		M	*SD*	*M*	*SD*	*M*	*SD*
Single-task	CF|LH|PV	1052	229	733	155	867	148
	LF|CH|PV	843	145	1032	205	903	165
Triple-task	CF|LH|PV	1189	234	1158	213	1536	307
	LF|CH|PV	1208	235	1289	269	1650	424

In summary, regardless of the response modality, the location task was always responded to the fastest, followed by the pitch task, and finally by the color task. After the response modality switched for the location and the color task, the participants seemed to prioritize the response order according to the stimulus and not according to the response modality. Therefore, neither of the two hypothesized response orders (pedal < vocal < manual vs. manual < pedal < vocal) seems to be generally applicable for the single-tasks.

2.2.2 The performance in the triple-task in mixed blocks

A repeated-measures ANOVA was calculated for the triple-task in mixed-blocks with the within-subject factor response modality (foot, hand, vs. voice), and S-R pairing (CF|LH|PV vs. LF|CH|PV). Only the within-factor response modality was significant, *F*(2,28) = 17.54, *p* < .001, η^2_p = 0.556. Despite changing the S-R parings in the visual tasks, no effects could be observed, neither for the main effect S-R pairing, *F*(1,14) = 3.70, *p* = .075, η^2_p = 0.209, nor for the interaction between response modality and S-R pairing, *F*(2,28) = 2.50, *p* = .100, η^2_p = 0.152.

The response modalities hand (*M* = 1223 ms) and foot (*M* = 1198 ms) were equally fast (*M* = -25 ms, *t*(28) = -0.339, *p* = .737, 95 % CI for *M* [-178 ms, 127 ms]), and both were faster than the response modality voice (*M* = 1593 ms), (hand: *M* = -370 ms, *t*(28) = -4.951, *p* < .001, 95 % CI for *M* [-522 ms, -217 ms], foot: *M* = -395 ms, *t*(28) = -5.291, *p* < .001, 95 % CI for *M* [-548 ms, -242 ms]). Descriptively we could observe that in both S-R pairings the location task was slightly faster than the color task. Furthermore, the pitch task was much slower, as seen in the main effect of the response modalities.

The prioritization of response order according to stimuli found in the single-tasks was not evident in the subtasks of the triple-task. Instead of prioritizing the stimuli, the two response modalities hand and foot were prioritized in both S-R pairings, which is more in line with response order 2 (manual < pedal < vocal) but is not fully supported due to the equally fast execution of pedal and manual responses. Further, this seems to suggest that the two visual tasks do not interfere with each other.

2.2.3 The calculation of triple-task costs

The triple-task costs (differences in the mean values) in Experiment 1 were exclusively calculated from the difference of triple- and single-task (both from mixed blocks), e.g., for the response modality hand the response time of the subtask hand in the triple-task minus the response time of the hand in the single-task was calculated.

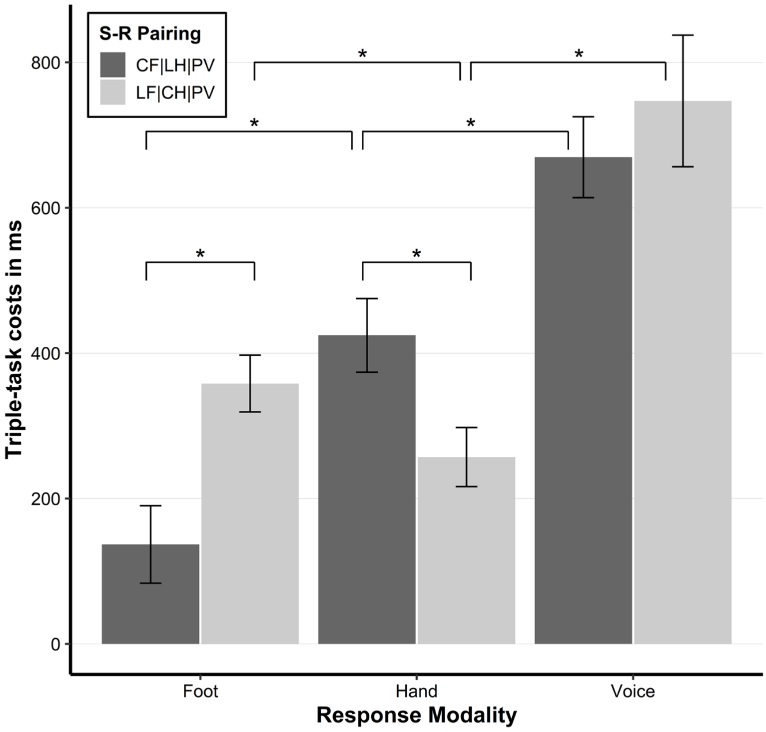

Figure 2: Triple-task costs in milliseconds to the foot (left), hand (middle), and voice response modality (right) as a function of the stimulus-response (S-R) pairings (color-foot, location-hand, and pitch-voice (CF|LH|PV) and location-foot, color-hand, and pitch-voice (LF|CH|PV)). The values (costs) were calculated from the subtask in the triple-task minus the corresponding single-task. Asterisks indicate significance (α = .05) of pairwise post hoc comparisons. Error bars represent +/-1 standard error of the mean.

A repeated-measures ANOVA was calculated for triple-task costs with response modality (foot, hand, vs. voice) and S-R pairing (CF|LH|PV vs. LF|CH|PV) as a within-subject factor. The main effect for response modality, $F(2,28) = 32.80$, $p < .001$, $\eta^2_p = 0.701$, was significant. The main effect for S-R pairing, $F(1,14) = 3.02$, $p = .104$ $\eta^2_p = 0.117$, was not significant. The interaction of response modality and S-R pairing, $F(2,28) = 11.17$, $p<.001$, $\eta^2_p = 0.444$, was significant.

The triple-task costs did not differ between response modality with the same stimuli (e.g., foot from S-R pairing CF|LH|PV vs. hand from S-R pairing LF|CH|PV) but between stimuli with the same response modality (e.g., color from S-R pairing CF|LH|PV vs. location from S-R pairing LF|CH|PV). The lowest costs occurred with the color stimulus (with $M_{\text{Foot}} = 137$ ms, $M_{\text{Hand}} = 257$ ms). This was followed by the location stimulus (with $M_{\text{Foot}} = 358$ ms, $M_{\text{Hand}} = 425$ ms) and the pitch stimulus with the highest costs (with $M_{\text{Pitch-CF|LH|PV}} = 670$ ms, $M_{\text{Pitch-LF|CH|PV}} = 747$ ms) (see Fig. 2).

Comparing the single tasks and the triple-task, significant costs were observed in each subtask, which - turned out to be the higher the later the subtask was responded to. Averaged over the two S-R pairings, this meant a doubling of the response times from the fastest subtask to the second-fastest subtask and from the second-fastest subtask to the slowest subtask.

2.3 Discussion

The aim of Experiment 1 was to examine the effects of three simultaneous tasks, allowing us to quantify the behavior of single-tasks and triple-tasks in a triple-task context. The results showed that in mixed blocks the response times in both single-tasks and the triple-task strongly increased and were up to two times higher compared with single-tasks in uniform blocks or in single-tasks and dual-tasks in other studies (Schumacher et al. 2001; Tombu and Jolicoeur 2004; Maquestiaux et al. 2018). It was further observed that participants responded in single-tasks fastest to the location stimulus and slowest to the color stimulus.

However, in the triple-task, the response to the location and color stimulus were apparently grouped (response times differences *M* = -25 ms) and showed similar response times (see section "The performance in the triple-task in mixed blocks"). Regardless of S-R pairing, the triple-task costs were lowest with the color stimulus, followed by the location stimulus, and the pitch stimulus. The apparent grouping of the response modalities hand and foot in the triple-task could have several reasons. Either (1) both tasks are actually processed in parallel, (2) crosstalk of stimuli and response codes prevents separate processing, or (3) the complexity of the triple-task requires different cognitive strategies than dual-tasks. The results of Experiment 1 currently allow the conclusion that both visual subtasks were processed simultaneously in the triple-task. According to the feature-integration theory of attention (Treisman & Gelade, 1980), both stimuli (location and color) can be perceived and processed simultaneously. But, in other studies that used the response modalities hand and foot in dual-tasks, there was no grouping in response times but sequential processing (Hoffmann et al., 2019; Liepelt, Fischer, et al., 2011; Sangals et al., 2007). However, the assumption that the response modalities hand and foot were processed simultaneously is rather weak as Liepelt et al. (2011) was unable to achieve complete elimination of dual-task costs despite intensive training, which argues against simultaneous processing. Liepelt et al. (2011) listed as a possible reason the crosstalk between the two tasks. In their study, the response codes shared the same (spatial) dimension resulting in interference between the two tasks (Hommel, 1998, 2019; Koch & Prinz, 2002). In our Experiment 1, both tasks shared the same dimension not only in the response codes but also in the stimuli codes. Thus, S-S and R-R compatibility may have occurred, strongly linking CF|LH, and LF|CH and preventing them from being processed separately. In addition, it is possible that the higher demands within a triple-task simply led to a strategy adaptation to process all tasks as quickly as only possible if subtasks were grouped (as may be the response modalities hand and foot). Thus, similar to bimanual coordination, response 1 waits for response 2, and both are executed more or less simultaneously although response 1 could already have been executed. The prerequisites are given by the temporal (SOA = 0 ms) and spatial (spatial) overlap (Miller & Ulrich, 2008; Rinkenauer et al., 2001). However, to find more evidence for the assumption these dual-tasks have to be added to compare them with the triple-task. This was done in Experiment 2.

3 Experiment 2

In Experiment 1, participants completed only single-tasks and triple-tasks. Unexpectedly, response times were very high in both the triple-task and the single-tasks, which complicated a comparison with other studies. Also, the costs (triple-task compared to single-tasks) were much higher than expected. The introduction of the three possible dual-tasks should provide a better explanation for the observed effects in Experiment 1. In the following Experiment 2, participants performed single-tasks, dual-tasks, and triple-tasks in a between-subject design either with the S-R pairing location-hand and color-foot, or location-foot and color-hand. Each pairing was combined with the pitch-voice pairing.

3.1 Methods

3.1.1 Participants

44 students (21 females, *M* = 22.30, *SD* = 2.35) took part in this experiment. Two participants were left-handed, 42 right-handed. All participants had a normal or corrected-to-normal vision and no hearing impairments. They provided informed consent and were given course credit or ~9 € as compensation for their participation. Due to error rates of up to 65 %, two participants were excluded. Thus, 42 participants were included in the final analysis.

3.1.2 Setup

For Experiment 2, we used the same setup as for Experiment 1.

3.1.3 Task

Dual-tasks were added in addition to the existing single-tasks and the triple-task. Any combination of single-tasks was possible. This resulted in the location + color, location + pitch, and color + pitch dual-task. Similar to Experiment 1, but in a between-subject design, stimulus-response mapping depended on the S-R pairing condition.

3.1.4 Design

Contrary to Experiment 1, in a between-subject design, participants completed only one of two S-R pairing conditions (color-foot, location-hand, and pitch-voice (CF|LH|PV) or location-foot, color-hand, and pitch-voice (LF|CH|PV)) in one session. The session consisted of seven different uniform blocks and six mixed blocks. A uniform block comprised of eight trials of only one type of single-tasks, dual-tasks, or the triple-task. All uniform blocks served only for the exercise of each trial type. The order was always single-task, dual-task, followed by the triple-task to allow participants to become familiar with the modified or additional tasks. A mixed block consisted of each of the three single-tasks and dual-tasks and the triple-task with a total of 24 single-tasks, 24 dual-tasks, and 24 triple-tasks in each block.

3.1.5 Analyses

As in Experiment 1, only correct trials were included in the analyses (error rate in single-tasks: 5.6 %, dual-tasks: 11.7 %, triple-task: 11.1 %). All trials with response times faster than 80 ms and slower than 4500 ms were removed (single-tasks: 1.7 %, dual-tasks: 3.8 %, triple-task: 5.9 %).

3.2 Results

In the following, we compared response times in all single- (ST), dual- (DT), and triple-tasks (TT) as well as task costs in the context of dual-task costs and triple-task costs. Based on Experiment 1, we did not focus on the analysis of the response modalities but the stimuli in a repeated-measures ANOVA with the within-subject factor task (single-tasks, location + color dual-task, location + pitch dual-task, color + pitch dual-task, and triple-task) as a factor and the between-subject factor S-R pairing (CF|LH|PV and LF|CH|PV) as for each stimulus (color, location, or pitch) individually, e.g. for the location stimulus the tasks single-task, location + color dual-task, location + pitch dual-task, and TT were included. All descriptive values except the between-subject factor stimulus-response Pairing (S-R pairing) are presented in Tables 2 and 3. As we found no significant influence of the between-subject factor S-R pairing in any of the subsequent analyses (all *p*s > .20), descriptive tables including this factor can be found in the supplementary material (see Tables S1 to S6 in the supplementary material).

3.2.1 Response order between single-, dual-, and triple-tasks

To compare response times, all single-, dual-, and triple-tasks were aggregated in each case. We calculated a repeated-measures ANOVA with the three tasks as within-subject factor (single-task, dual-task, tiple-task). The analysis showed a significant main effect, $F(2,82) = 370.0$, $p < .001$, $\eta^2_p = 0.900$. Single-task were significant slower than dual-tasks, M = -457 ms, t(41) = -19.2, p < .001, 95% CI [-505 ms, -409 ms], and the triple-task, M = -653 ms, t(41) = -21.4, p < .001, 95% CI

Table 2: Mean response times (calculated from participants' means) and standard deviations in milliseconds for single-task trials, dual-task trials, and triple-task trials from mixed blocks.

Task	Combination	Color		Location		Pitch	
		M	*SD*	*M*	*SD*	*M*	*SD*
Single-task	-	874	171	689	154	941	185
Dual-task	Location + Color	1240	263	1236	280	-	-
	Location + Pitch	-	-	981	291	1447	311
	Color + Pitch	1243	298	-	-	1602	355
Triple-task	-	1326	296	1316	306	1819	357

Table 3: Mean error rates (calculated from participants' means) and standard deviations for single-task trials, dual-task trials, and triple-task trials from mixed blocks. Numbers indicate % values.

Task	Combination	Color		Location		Pitch	
		M	*SD*	*M*	*SD*	*M*	*SD*
Single-task	-	6.5	6.4	5.3	7.6	3.0	3.7
Dual-task	Location + Color	7.5	6.6	3.8	4.6	-	-
	Location + Pitch	-	-	1.3	1.7	8.6	7.6
	Color + Pitch	7.8	7.5	-	-	8.0	6.9
Triple-task	-	4.9	4.2	1.7	1.9	4.2	3.9

[-715 ms, -591 ms]. The dual-task were also significant slower than triple-tasks, M = -196 ms, t(41) = -10.9, p < .001, 95% CI [-232 ms, -160 ms].

The average response times of all dual-tasks (*M* = 1292 ms) relative to all single-tasks (*M* = 834 ms) increased by *M* = 457 ms. For all triple-tasks (*M* = 1487 ms), this increased by 196 ms or ~43% relative to all dual-tasks. Thus, response times increased less than linearly. However, examination of these costs in relation to the stimuli revealed widely varying costs depending on the specific task.

3.2.2 Response order within single-, dual-, and triple-tasks

Single-Tasks. To identify prioritization of (sub-) tasks we calculated a repeated-measures ANOVA with the three single-tasks as within-subject factor (color task, pitch task, location task). The analysis showed a significant main effect, *F*(2,82) = 43.0, *p* < .001, η^2_p = 0.512. The location-single-task was on average processed fastest (689 ms), followed by the color-single-task (874 ms), location compared to color: *M* = -186 ms, *t*(82) = -6.58, *p* < .001, 95% CI [-242 ms, -129 ms], and the pitch-single-task (941 ms), color compared to pitch: *M* = -67 ms, *t*(82) = -2.36, *p* = .021, 95% CI [-123 ms, -10 ms] (see all results in Table S7 in the supplementary material).

In single-tasks, the response order was not stable across both experiments. Compared to Experiment 1, the participants now prioritized responses in a different order changed from location < pitch < color to location < color < pitch in Experiment 2.

Dual-Tasks. In the dual-tasks, the paired *t*-tests showed no difference between the color sub-task and the location sub-task in the location + color dual-task, *M* = 4 ms, *t*(41) = 0.18, *p* = .859, 95% CI [-40 ms, 48 ms]. However, a significant difference between two sub-tasks was observed in the location + pitch dual-task, *M* = -466 ms, *t*(41) = -13.47, *p* < .001, 95% CI [-536 ms, -396 ms], and in the color + pitch dual-task, *M* = -359 ms, *t*(41) = -11.87, *p* < .001, 95% CI [-420 ms, -298 ms].

In dual-tasks, we observed that neither the location task nor the color task was preferred when they appeared in the same dual-task. But in combination with the pitch task, the location and color tasks were always preferred.

Triple-Task. The same analysis as for the single-tasks was calculated for the triple-task with the three subtasks as within-subject factor, which revealed a similar pattern. We could observe a significant main effect, $F(2,82) = 103.0$, $p < .001$, $\eta^2_p = 0.714$, but the difference between the color and the location sub-tasks was not significant, $M = 10$ ms, $t(82) = 0.25$, $p = .805$, 95% CI [-70 ms, 90 ms]. The pitch task was still the slowest (see Table S7).

It seems that when combining the response modalities hand and foot in both the location + color dual-task and the triple-task, the responses times were equally fast. Consequently, we could not observe a clear task prioritization of the (sub-) tasks like Hoffmann et al. (2019) where participants responded fastest to oculomotor than pedal < vocal < manual (for a different response order see also Hazeltine et al., 2002).

3.2.3 Error rates within single-, dual-, and triple-tasks

Single-Tasks. For error rates in single-tasks the main effect was significant, $F(2,82) = 5.50$, $p = .006$, $\eta^2_p = 0.121$. We observed the lowest rates with the pitch stimulus ($M = 3.0$ %), pitch compared to color: $M = -3.5$ %, $t(41) = 4.16$, $p < .001$, 95% CI [-5.2 %, -1.8 %] followed, but without difference, by the color ($M = 6.5$ %) and location ($M = 5.3$ %) stimulus, color compared to location: $M = 1.2$ %, $t(41) = 0.94$, $p = .351$, 95% CI [-1.4 %, 3.9 %] (see all results in Table S8).

The error rates in the single-tasks showed the opposite pattern to the response times. While the response times in the pitch task were the highest, the error rates were now the lowest.

Dual-Tasks. Contrary to the response times in the location + color dual-task, significant difference in error rates were observed between the location ($M = 7.5$ %) and color ($M = 3.8$ %) stimulus, $M = 3.7$ %, $t(41) = 4.91$, $p < .001$, 95% CI [2.2 %, 5.2 %]. Furthermore in the location + pitch dual-task, the error rates with the location stimulus ($M = 1.3$ %) were lower than with the pitch stimulus ($M = 8.6$ %), $M = -7.4$ %, $t(41) = 4.91$, $p < .001$, 95% CI [-9.7 %, -5.1 %]. In the color + pitch dual-task, no difference in error rates between the stimuli were observed (($M_{\text{color}} = 7.8$ %, $M_{\text{pitch}} = 8.0$ %), $M = -0.4$ %, $t(41) = -0.34$, $p = .74$, 95% CI [-1.7 %, 1.2 %].

The error rates in the dual-tasks appeared very unsystematic in the current data sample. It should be emphasized, however, that the error rate in the location + color dual-task differed significantly, indicating interference between the two subtasks compared to the response times.

Triple-Task. In the triple-task, the main effect was significant, $F(2,82) = 23.2$, $p < .001$, $\eta^2_p = 0.361$. The location stimulus ($M = 1.7$ %) showed the lowest error rates followed by the color stimulus ($M = 4.9$ %), location compared to color: $M = -3.2$ %, $t(41) = 6.3$, $p < .001$, 95% CI [-4.2 %, -2.2 %], and pitch stimulus ($M = 4.2$ %) , color compared to pitch: $M = 0.7$ %, $t(41) = 1.61$, $p = .116$, 95% CI [-0.2 %, 1.5 %] (see all results in Table S8 in the supplementary material).

In comparison to the dual-tasks, the subtasks in the triple-task again showed a different pattern. The error rate increased comparable to the response times in the same subtasks (location < color < pitch).

3.2.4 Triple-task and dual-task costs

3.2.4.1 Response times

Based on the results of the single-task, dual-task, and triple-task trials, different dual- and triple-task costs could be calculated in Experiment 2. We always compared the occurring stimulus in the respective dual-task or triple-task to the single-task (e.g., in the dual-task location-color the sub-task with the color stimulus and the single-task with the color stimulus). The resulting costs can be seen in Fig. 3 and Fig. 4.

For each stimulus (color, location, and pitch), repeated-measures ANOVAs with the task as a within-subject factor (dual-task location + color, dual-task location + pitch, dual-task color + pitch, and the triple-task) were calculated. However, the corresponding task was only analyzed if the corresponding stimulus was also present in the task. Significant main effects were found for all stimuli (see Table S9 in the supplementary material).

For the *color stimulus*, participants showed equally high costs, in both dual-tasks (color + location $M_{\text{color}} = 366$ ms; color + pitch $M_{\text{color}} = 369$ ms), $M = -3$ ms, $t(82) = -0.11$, $p = .913$, 95% CI [-54 ms, 48 ms]. Only the triple-task costs ($M_{\text{color}} = 452$ ms) were significantly higher than both dual-task costs, location + color dual-task costs compared to triple-task

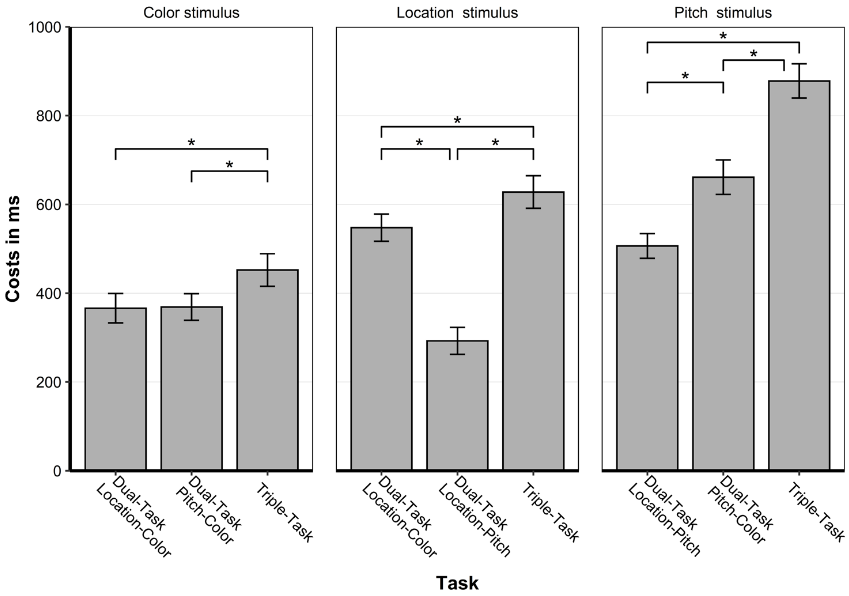

Figure 3: Dual-task costs and triple-task costs to the color stimulus (left), location stimulus (middle), and pitch stimulus (right) as a function of the task (location + color, color + pitch, location + pitch dual-task, and triple-task) in which they are appearing (e.g. in the leftmost bar, the cost was calculated from the location + color dual-task minus the color single-task). Thus, values represent dual-task costs and triple-task costs compared to single-tasks (averaged over stimulus-response (S-R) pairing condition). Asterisks indicate significance (α = .01) of pairwise post hoc comparisons. Error bars represent +/-1 standard error of the mean.

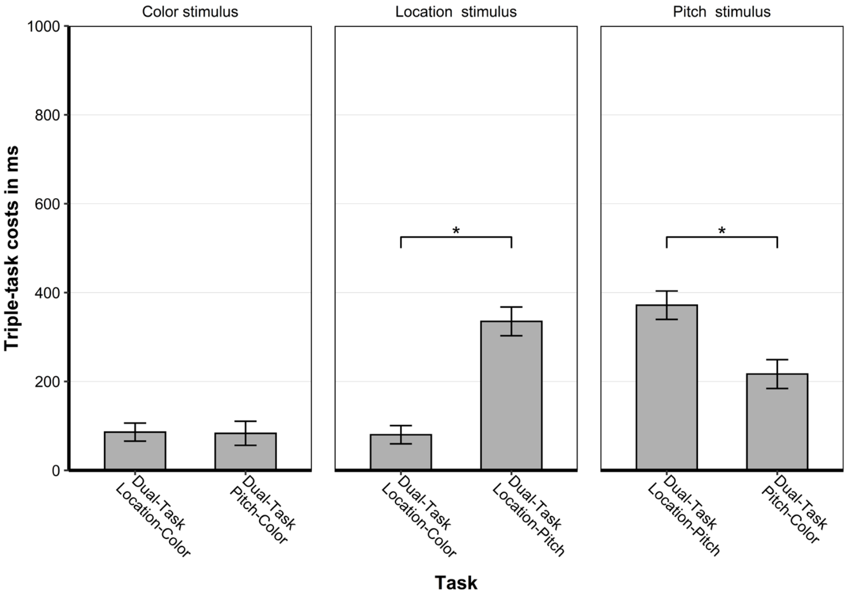

Figure 4: Triple-task costs to the color stimulus (left), location stimulus (middle), and pitch stimulus (right) as a function of the task (location + color, color + pitch, and location + pitch dual-task) in which they are appearing (e.g., the leftmost bar, the response time was calculated from the color task from the location + color dual-task minus the triple-task with a color stimulus). Thus, response times represent triple-task costs compared to dual-tasks (averaged over stimulus-response (S-R) pairing condition). Asterisks indicate significance (α = .01) of pairwise post hoc comparisons. Error bars represent +/-1 standard error of the mean.

costs: M = -86 ms, $t(82)$ = -3.37, p = .001, 95% CI [-137 ms, -35 ms] and color + pitch dual-task costs compared to triple-task costs: M = -83 ms, $t(82)$ = -3.26, p = .002, 95% CI [-134 ms, -32 ms].

For the *location stimulus*, the lowest costs were found for the location + pitch dual-task (M_{location} = 293 ms), which were significantly lower than the costs for the location + color dual-task (M_{location} = 548 ms), M = -255 ms, $t(82)$ = -8.69, p < .001, 95% CI [-313 ms, -197 ms]. As with the color stimulus, the triple-task costs were highest (M_{location} = 628 ms), location + color dual-task costs compared to triple-task costs: M = -80 ms, $t(82)$ = -2.73, p = .008, 95% CI [-139 ms, -22 ms].

For the *pitch stimulus*, a comparable pattern as for the location stimulus emerged. In the location-pitch dual-task (M_{pitch} = 506 ms) participants showed the lowest costs. Significantly higher costs were again observed in the color-pitch dual-task (M_{pitch} = 661 ms), M = -155 ms, $t(82)$ = -4.74, p < .001, 95% CI [-220 ms, -90 ms], and with the highest costs in the triple-task (M_{pitch} = 878 ms), color + pitch dual-task costs compared to triple-task costs: M = -217 ms, $t(82)$ = -6.63, p < .001, 95% CI [-282 ms, -152 ms].

Depending on the dual-task, there were different costs in relation to the respective single-task. For the color stimulus, each response modality produced the same costs. However, dual-tasks that required responding to location or pitch showed that the stimulus combination of location and pitch had the lowest costs, and in combination with color, the higher costs were incurred. For all possible combinations, the triple-task costs relative to the single-tasks were always higher than triple-task costs relative to dual-task costs (meaning the triple-task always produced additional costs). These increased much less than the dual-tasks except when compared to tasks with the pitch stimulus. This argues against purely additive increase from dual-task costs to triple-task costs. To test this, we analyzed the costs of the subtasks within the three dual-tasks.

The triple-task costs of the location and color stimuli in the location + color dual-task, showed no differences, M = -6 ms, $t(41)$ = -0.69, p = .494, 95% CI [-24 ms, 12 ms], also the comparison of triple-task costs between the location and pitch stimuli in the location + pitch dual-task, M = -37 ms, $t(41)$ = -1.45, p = .156, 95% CI [-87 ms, 14 ms]. This means that the response times increased from the dual-task to the triple-task by the same amount in both subtasks. Only in the color-pitch dual-task the costs increased more for the pitch stimulus task than for the color stimulus task in the color + pitch dual-task, M = -133 ms, $t(41)$ = -5.36, p < .001, 95% CI [-184 ms, -83 ms].

3.2.4.2 Error Rates

We calculated the same ANOVAs for the triple-task costs and dual-task costs of error rates. Significant main effects emerged across all three stimuli (see Table S10 in the supplementary material). The descriptive is reported in Table 4. For the *color stimulus*, M = -0.3 %, $t(41)$ = -0.21, p = .838, 95% CI [-3.1 % 2.5 %], and pitch stimulus, M = 0.6 %, $t(41)$ = 0.45, p = .653, 95% CI [-2.1 % 3.4 %], we observed high costs with dual-task, but they were equal compared to each other. The costs for the triple-task (< 1.6%) was significantly lower compared to both dual-tasks costs (see details in Table S11 in the supplementary material). However, for the *location stimulus*, dual-task costs differed significantly between location + color dual-task (M = -1.4%) and location + pitch dual-task (M = -4.0 %), M = 2.6 %, $t(41)$ = 3.81, p < .001, 95% CI [1.2 % 3.9 %]. Here, location + pitch dual-task was equally low as triple-task (M = -3.6 %), M = -0.5 %, $t(41)$ = -1.11, p = .274, 95% CI [-1.3 % 0.4 %].

While the response times increased significantly from the single-tasks to the triple-tasks, this trend was not observed for the error rates.

We also calculated the costs in the subtasks within the three dual-tasks. Error rate costs decreased uniformly across stimuli from dual-tasks to the triple-task (comparable to the uniform increase in response time costs). Only the location + pitch dual-task showed a greater reduction in cost for the pitch stimulus (M_{Location}= -4.4 %) than for the location stimulus (M_{Location}= 0.5 %), M = 4.9 %, $t(41)$ = 4.87, p < .001, 95% CI [2.9 %, 6.9 %].

3.3 Discussion

In Experiment 2, in addition to the three single-tasks and the triple-task from Experiment 1, three additional dual-tasks were performed. These tasks occurred in a between-subjects design either in the stimulus-response pairing (S-R pairing) location + hand, color + foot, and voice + pitch or location + foot, color + hand, and voice + pitch. However, the analyses of the response times did not show any difference in the S-R pairings, therefore these were not considered

Table 4: Triple-task costs, dual-task costs, and standard deviation of error rates in comparison with single-tasks and triple-task costs and standard deviation of error rates in comparison with dual-tasks. Triple-tasks, dual-tasks, and single-tasks were always compared with the same stimulus (e.g. the color task in the triple-task with the color task in the single-task).

Compared Stimulus	**Color**		**Location**		**Pitch**	
	Triple-task costs					
	M	*SD*	*M*	*SD*	*M*	*SD*
Difference to	Triple-task					
Single-task	-1.6	4.6	-3.6	7.7	1.2	2.6
Location + color dual-task	-2.6	5.6	-2.1	4.5	-	-
Location + pitch dual-task	-	-	0.5	2.7	-4.4	6.3
Color + pitch dual-task	-2.9	6.0	-	-	-3.8	5.1
	Location + color dual-task costs					
Difference to	Location + color dual-task					
Single-task	1.0	6.2	-1.4	7.8	-	-
	Location + pitch dual-task costs					
Difference to	Location + pitch dual-task					
Single-task	-	-	-4.0	6.8	5.7	6.5
	Color + pitch dual-task costs					
Difference to	Color + pitch dual-task					
Single-task	1.3	6.1	-	-	5.1	5.7

further in the calculation of the dual-task and triple-task costs. Thus, the determining factors were not the response modalities but the stimuli. The response times were fastest in the single-tasks, followed by the dual-tasks and with the slowest response times in the triple-task. In contrast to the response times, the error rates decreased from single- to dual- to triple-tasks. Initially, a strong increase in errors was expected when more tasks were presented at the same time. However, the very low error rates in the triple-tasks can possibly be attributed to a higher level of attention and concentration. Furthermore, if all effectors are always prepared in mixed blocks, then in the triple-task, none of the effectors had to be suppressed. It can be assumed that all three subtasks were always prepared before each task and when less than three tasks occurred (triple-task) the others had to be suppressed (cf. Hirsch et al., 2021; Schumacher & Hazeltine, 2016).

Comparing single-, dual-, and triple-tasks directly, we observed in the response times as well as in the costs that both increased more from single-tasks to dual-tasks than from dual-tasks to triple-tasks. Consequently, we could not observe a linear increase between the three tasks since this would have implied that the increase would always have been the same. If we assume that the increase from single-tasks to dual-tasks was 100%, we could only observe an increase of 43% in the response times from the dual-tasks to the triple-tasks. Furthermore, the dual-task in comparison to the single-tasks costs showed that the costs in both subtasks were the same, only in the dual-task color-pitch the costs in the pitch and color task increased differently.

4 General Discussion

This study aimed to examine the additional complexity of another simple task added to a classical dual-task paradigm, allowing us to quantify the progression of response times and costs. In Experiment 1 (E1) participants performed single-tasks and triple-tasks which were complemented by dual-tasks in Experiment 2 (E2).

4.1 Response order in Single-Tasks, Dual-Tasks, and the Triple-Task

In single-tasks, the average response times for the stimuli could be ordered as follows: in E1: location < pitch < color (manual/pedal < vocal < pedal/manual) and in E2: location < color < pitch (manual = pedal < vocal). Hence, both of our assumptions about the response order were wrong, which underlines the usefulness of testing these assumptions as we have done. Modality-compatible tasks (in the present study the location task with response modalities hand or foot and the pitch task with the response modality voice) were expected to be faster than tasks with ideomotor incompatibility (color task with response modality hand or foot) (Göthe et al., 2016; Hazeltine et al., 2006; Koch, 2009; Stephan et al., 2021; Stephan & Koch, 2010). However, the difference in response order could be due to the fact that participants in E1 had to complete both S-R pairings and thus strategic responding played a less prominent role (compared to triple-tasks). In E2, due to the triple-tasks, the focus was assumably more on the hand and foot response modalities, which was also evident in the single-tasks.

In triple-tasks, the pattern of response times was similar in both experiments. The location and color stimuli were responded with equal priority and the response time for the pitch stimulus was the slowest. We originally expected clear sequential processing of the stimuli to avoid a bottleneck, specifically not only to avoid crosstalk between the two visual tasks (Hommel, 2019; Koch, 2009) but also to reduce the coordinative complexity (Logan & Gordon, 2001). Based on similar observations for the two response modalities hand and foot, it seems like that coordination of these two response modalities took place first, similar to studies of bimanual coordination (Franz et al., 2001; Miller & Ulrich, 2008; Ruthruff et al., 2001). Similarly, studies with piano players showed that participants were able to perform better (fewer errors) when both hands acted in concert (e.g., when the hands produce a common rhythm and not two separate rhythms). An indication of the changed response order or rather grouping of visual tasks could be also found in studies on coordination skills. Liepelt et al. (2011) and Strobach et al. (2015) compared training with simultaneous dual-tasks and training with single-tasks and both found a superior effect from training the dual-tasks in a mixed block as opposed to training the two single-tasks separately in a uniform block. The benefit from dual-task training in mixed blocks may be due to the necessity that the combination of two tasks to a dual-task affords extra coordination to treat the two tasks as one task. If this assumption is true, it may also hold for the triple-task with the difference that three single-tasks have now to be treated as one task. This affords more coordination in comparison to dual-tasks and participants must optimize coordination (similar to bimanual coordination). One strategy is to pack effector procedures together into one procedure that is paired with the same type of stimulus. In the case of the triple-task, this is the pairing of the visual stimuli with those motor effectors that are intended to change the state of an object like the button and the pedal. In their review, Strobach and Schubert (2017a) discussed similar mechanisms in the training of dual-tasks, supporting this assumption. If few resources are available and the participants are given the freedom to decide which task should be prioritized, they can train their attention allocation and task coordination. As a result, a high level of efficiency is achieved in the retrieval of task rules and coordination. Further post hoc analyses support this assumption. It was found that only two participants[1] did not group the hand and foot subtask in the triple-task ($RT_{hand} - RT_{foot} <= 100$ ms). However, on average across all participants, in 84% (*SD* = 20%) of all triple-tasks, both subtasks were grouped. Another argument in favor of a strategic response to the tasks is the fact that the cost from location + color dual-task to the triple-task (triple-task cost) was less than 80 ms. These were still significant costs, but compared to the increase in costs from the single-tasks (location and color) to the location + color dual-task with more than 360 ms, this was only a very small increase and almost met Kieras et al.' criterion (2000) of simultaneous processing (costs < 50 ms). Adapted from inhibition in task-switching paradigms (see Koch et al., 2010, e.g.), one could argue that in the mixed blocks all three

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[1] In the triple-task, the two participants responded with the hand response modality (*M* = 808 ms) the fastest, followed by the foot response modality (*M* = 1231 ms) and with a response time almost twice as high voice response modality (*M* = 2118 ms).

responses (manual, pedal and voice) had to be prepared on every trial and in dual-tasks, the non-demanded task had to be suppressed, so it was similar to a triple-task requiring two responses and one suppression (e.g. in a location + color dual-task, participants had to respond with their hand and foot while the voice response had to be actively suppressed).

In dual-tasks, as already mentioned, the response times in all dual-tasks were higher than in comparable studies with similar dual-tasks, but only in the location + color dual-task, both subtasks showed similar response times to the subtasks in the triple-task. In the other two dual-tasks, the response times in at least one subtask were significantly faster (> 300 ms) than in the triple-task. Thus, the results tend to argue for strategic coordination of tasks across all task types and neither suppression nor integration of tasks. This is also supported by the error rates. Participants almost always made the fewest errors in the triple-task.

4.2 Dual-Task and Triple-Task costs

The calculation of dual-task costs is defined in most dual-task studies by the difference between dual- and single-tasks (Hazeltine et al., 2002, e.g.). If this difference is no longer significant, it is often referred to as *perfect time-sharing*, i.e., the task runs equally fast in both conditions (dual-task vs. single-task). However, *perfect time-sharing* in both subtasks can only be achieved by extensively training the dual-tasks and the single-tasks (Schumacher et al., 2001). For triple-task costs, there are several possibilities for computing these costs. Thus, the subtasks of the triple-task can not only be compared with the single-tasks but also with the three possible dual-tasks (see Table A1 in the appendix). In our results, comparing the dual- and the triple-tasks with the single-tasks showed, as expected, very high costs, which were highest with respect to the triple-tasks. However, when comparing the triple- with the dual-tasks, we observed that the costs increased differently depending on the dual-task. When we compared the triple-task to the location (M = 335 ms) + pitch (M = 372 ms) dual-task or location (M = 80 ms) + color (M = 86 ms) dual-task, similar triple-task costs were observed in all subtasks but not for the subtasks in the pitch (M = 217 ms) + color (M = 83 ms) dual-task. Thus, the amount of cost depended on which dual-task the subtask occurred and did not generally increase at the same rate across all tasks. One possible reason for the widely differing costs may be explained as followed: in previous studies, the location + pitch dual-task performed most efficiently in terms of the dual-tasks, i.e. the lowest costs were observed because of modality compatible S-R pairings (Hazeltine et al., 2006). Modality compatible tasks refer to the processing of stimuli and responses working best in their respective combinations (location – hand and pitch – voice). For the location + color and color + pitch dual-task, we also had ideomotor compatibility, but they were probably influenced by strategies. So, both dual-tasks may have been strongly influenced by the strategies already in use, i.e., the coordination of the hand and foot response modalities. This could be seen in the location + color dual-tasks where the two subtasks were grouped which led to the fact that the response times and costs of both subtasks did not greatly increase in the triple-task. Especially since the response time in the location + color dual-task could have been much faster than it ended up being. That the response time in the location and color subtasks could be faster, was seen in the response times in the other two dual-tasks, where both were much faster. Consequently, the strategy of the location + color dual-task might also have affected the color + pitch dual-task. Although the color task was not ideomotor compatible, this subtask was processed first, which led to a strong delay of the ideomotor compatible task with the pitch. The present data indicate that task coordination arguably has a major impact on triple-task processing. In this study, the data were collected in only one session. However, studies on dual-tasks show that training over several sessions changes and ultimately improves task coordination (see review, Strobach & Schubert, 2017a). At this point, it would be interesting to find out to what extent training influences task coordination in triple-tasks.

4.3 The Triple-Task in the Context of Different Models

One of the most widespread structural models of dual-task processing assumes a response selection bottleneck (RSB) (Pashler 1994, 1990, 1984). The RSB can process only one task per time frame and is presumed to be located in the central system. The model assumes that only at the peripheral stages (perception and motor execution), two tasks could run at the same time. Applied to the triple-task, a clear sequence of responses to the subtasks should now have become apparent as a result of the central bottleneck. But we could not observe this in our experiments, not even for both the visual tasks. The two visual tasks were responded to almost simultaneously. However, this observation is not an argument against the RSB. For performing a dual-task Ruthruff et al. (2001) instructed participants explicitly to respond to both stimuli simultaneously. They could detect massive interference. Participants needed much longer to respond to both tasks than for the single-tasks. They regarded this as clear evidence for the RSB. This would also explain why the response times of the triple-task were so high compared to single-tasks. In order to test this theory in more detail, further experiments would have to be carried out, e.g. with different SOAs.

Resource models also provide explanations for interferences with dual-tasks. The advantage of these models is that they assume the ability to flexibly divide resources (whatever resources are). A single-task can be processed with 100%, but two or more tasks must share the resource. When processing several tasks at the same time, 100% is now divided by the number of tasks (Norman & Bobrow, 1975). On this basis, Tombu and Jolicœur (2003) developed the central capacity-sharing model (CCS). Now, dual-tasks could theoretically run at the same speed as single-tasks. CSS would now explain why the response time for the triple-task increased that much, but it also does not provide clear assumptions about why subtasks are coordinated differentially in dual-, triple- or what seems to be generalizable in multi-tasks.

4.4 Perspectives on triple-tasks

The higher goal of this study is to shrink the gap between laboratory studies and real-world applications (also simulators). Thus, it should be discussed what a task, which can also consist of several subtasks, is. While some assume that driving a car, for example, is a (single-) task, this can also be seen as multiple tasks. Depending on the instruction, even a simple dual-task can be seen as processing two tasks or just one task (see studies on manipulation of instruction). There are now three perspectives on our triple-task.

As discussed in detail before, the triple-task is a task that is coordinated in terms of effectors. This results in a logical sequence of pedal/manual - vocal in the task for the participant. The increased response times thus arose from coordination. This suggests that more complex tasks are combined into one task in order to be able to act more quickly and without errors. The worse performance in the single- and dual-tasks may also be due to the triple-task, which is regarded as one, having to be “disassembled” again, which leads to higher error rates and response times.

Another perspective, especially with regard to the strongly increased response times, can also be found in the high number of S-R pairings to be remembered (cf. Wühr & Biebl, 2011). Duncan et al. (2008) were able to show that in a complex task with multiple components, some were neglected even though participants knew the rules for the neglected task. All facts, rules, and requirements are stored in a task model. However, with increasing complexity, these can compete with each other, which leads to the loss of vulnerable components. In our experiments, all tasks have to be stored in the task model, which can lead to an overload of the working memory due to the number of rules and S-R pairings. In the case of triple-tasks, the consequence is not that a task is necessarily neglected, but that more errors occur when switching between single-, dual-, and triple-tasks. The more rules, i.e. S-R pairings, can be retrieved, the worse the performance (Wühr & Biebl, 2011).

Another view is that tasks are organized hierarchically not on a local but on a global level (Schumacher & Hazeltine, 2016). The activation (task) is stored in a task file, which is similar to the event files in TEC (Hommel, 2019). The information in the task file, between the stimulus and the response, can be bidirectional, i.e. it can flow in both directions. The characteristic is that not a certain mechanism is specified, but a range of processes are deposited, which depend on the task. In the case of the triple-task, the highest priority (and also in the ideal case) would be to respond to it as quickly and error-free as possible. To do this, it is necessary to know the rules (which stimulus to respond to and what the possibilities are), as well as the allowed responses and the presented stimuli. Hirsch et al. (2018, 2021) also see evidence for a hierarchical organization of (dual-)tasks. Specifically, this would mean that even identical tasks achieve different response times, if they are combined and have to be coordinated into a different task model, which we observed in the single-, dual-, and triple-tasks in this study compared to other studies. All task types are thus stored in a single task file and are already activated before each task, which means that all tasks - even “pure” single- and dual-tasks - are only subtasks of the triple-task and therefore lead to longer response times when not needed. (cf. Hirsch et al., 2021).

5 Conclusion

In the present study, we extended the classical dual-task paradigm by a third task. In classical dual-tasks, the first response is indicated similarly fast as compared to single-tasks and only the second response is delayed. In a triple-task setting, all three responses are delayed. Additionally, in the triple-task, modality compatibility and ideomotor compatibility played less of a role as compared to classical dual-task studies which call their general theoretical significance into question. Both visual tasks in the triple-task were responded to equally fast, which is surprising since earlier work hypothesized a clear response order to emerge. Here, we discuss that the effects shown occurred due to differences in task coordination. Overall, our study showed that laboratory-based multitasking research is clearly limited by the restriction to only two tasks and generalization of such results to real-world multitasking should be drawn carefully. Multitasking research would benefit from an extended focus on strategically investigating settings involving more than two tasks.

Declarations

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Animal Rights: This article does not contain any studies with animal subjects performed by the any of the authors.

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References

Bherer, L., Kramer, A. F., Peterson, M. S., Colcombe, S., Erickson, K., & Becic, E. (2005). Training effects on dual-task performance: Are there age-related differences in plasticity of attentional control? *Psychology and Aging*, *20*(4), 695–709. https://doi.org/10.1037/0882-7974.20.4.695

Bherer, L., Kramer, A. F., Peterson, M. S., Colcombe, S., Erickson, K., & Becic, E. (2008). Transfer effects in task-set cost and dual-task cost after dual-task training in older and younger adults: Further evidence for cognitive plasticity in attentional control in late adulthood. *Experimental Aging Research*, *34*(3), 188–219. https://doi.org/10.1080/03610730802070068

Duncan, J., Parr, A., Woolgar, A., Thompson, R., Bright, P., Cox, S., Bishop, S., & Nimmo-Smith, I. (2008). Goal neglect and Spearman's g: Competing parts of a complex task. *Journal of Experimental Psychology: General*, *137*(1), 131. https://doi.org/10.1037/0096-3445.137.1.131

Franz, E. A., Zelaznik, H. N., Swinnen, S., & Walter, C. (2001). Spatial Conceptual Influences on the Coordination of Bimanual Actions: When a Dual Task Becomes a Single Task. *Journal of Motor Behavior*, *33*(1), 103–112. https://doi.org/10.1080/00222890109601906

Göthe, K., Oberauer, K., & Kliegl, R. (2016). Eliminating dual-task costs by minimizing crosstalk between tasks: The role of modality and feature pairings. *Cognition*, *150*, 92–108. https://doi.org/10.1016/j.cognition.2016.02.003

Gutzwiller, R. S., Wickens, C. D., & Clegg, B. A. (2019). The role of reward and effort over time in task switching. *Theoretical Issues in Ergonomics Science*, *20*(2), 196–214. https://doi.org/10.1080/1463922X.2018.1522556

Hackman, J. R. (1969). Toward understanding the role of tasks in behavioral research. *Acta Psychologica*, *31*, 97–128. https://doi.org/10.1016/0001-6918(69)90073-0

Hazeltine, E., & Ruthruff, E. (2006). Modality pairing effects and the response selection bottleneck. *Psychological Research*, *70*(6), 504–513. https://doi.org/10.1007/s00426-005-0017-3

Hazeltine, E., Ruthruff, E., & Remington, R. W. (2006). The role of input and output modality pairings in dual-task performance: Evidence for content-dependent central interference. *Cognitive Psychology*, *52*(4), 291–345. https://doi.org/10.1016/j.cogpsych.2005.11.001

Hazeltine, E., Teague, D., & Ivry, R. B. (2002). Simultaneous dual-task performance reveals parallel response selection after practice. *Journal of Experimental Psychology: Human Perception and Performance*, *28*(3), 527–545. https://doi.org/10.1037//0096-1523.28.3.527

Hirsch, P., Nolden, S., Philipp, A. M., & Koch, I. (2018). Hierarchical task organization in dual tasks: Evidence for higher level task representations. *Psychological Research*, *82*(4), 759–770. https://doi.org/10.1007/s00426-017-0851-0

Hirsch, P., Roesch, C., & Koch, I. (2021). Evidence for a multicomponent hierarchical representation of dual tasks. *Memory & Cognition*, *49*(2), 350–363. https://doi.org/10.3758/s13421-020-01097-3

Hirst, W., Spelke, E. S., Reaves, C. C., Caharack, G., & Neisser, U. (1980). Dividing Attention Without Alternation or Automaticity. *Journal of Experimental Psychology: General*, *1*(109), 98–117. https://doi.org/10.1037/0096-3445.109.1.98

Hoffmann, M. A., Pieczykolan, A., Koch, I., & Huestegge, L. (2019). Motor sources of dual-task interference: Evidence for effector-based prioritization in dual-task control. *Journal of Experimental Psychology. Human Perception and Performance*, *45*(10), 1355–1374. https://doi.org/10.1037/xhp0000677

Hommel, B. (1998). Automatic Stimulus-Response Translation in Dual-Task Performance. *Journal of Experimental Psychology: Human Perception and Performance*, *24*(5), 1368–1384. https://doi.org/10.1037/0096-1523.24.5.1368

Hommel, B. (2019). Theory of Event Coding (TEC) V2.0: Representing and controlling perception and action. *Attention, Perception, & Psychophysics*, *81*(7), 2139–2154. https://doi.org/10.3758/s13414-019-01779-4

Hommel, B. (2020). Dual-Task Performance: Theoretical Analysis and an Event-Coding Account. *Journal of Cognition*, *3*(1), 29. https://doi.org/10.5334/joc.114

Hommel, B., Müsseler, J., Aschersleben, G., & Prinz, W. (2001). The Theory of Event Coding (TEC): A framework for perception and action planning. *The Behavioral and Brain Sciences*, *24*(5), 849–878; discussion 878-937. https://doi.org/10.1017/s0140525x01000103

Huestegge, L., & Hazeltine, E. (2011). Crossmodal action: Modality matters. *Psychological Research*, *75*(6), 445–451. https://doi.org/10.1007/s00426-011-0373-0

Huestegge, L., & Koch, I. (2013). Constraints in task-set control: Modality dominance patterns among effector systems. *Journal of Experimental Psychology: General*, *142*(3), 633–637. https://doi.org/10.1037/a0030156

Kahneman, D. (1973). *Attention and effort*. Prentice Hall.

Kieras, D. E., Meyer, D. E., Ballas, J. A., & Lauber, E. J. (2000). Modern Computational Perspectives on Executive Mental Processes and Cognitive Control: Where to from Here? In S. Monsell & J. Driver (Eds.), *Control of Cognitive Processes. Attention and Performance XV/II: Vol. Attention and Performance XVIII* (pp. 681–712). MIT Press.

Kiesel, A., Steinhauser, M., Wendt, M., Falkenstein, M., Jost, K., Philipp, A. M., & Koch, I. (2010). Control and interference in task switching–a review. *Psychological Bulletin*, *136*(5), 849–874. https://doi.org/10.1037/a0019842

Koch, I. (2009). The role of crosstalk in dual-task performance: Evidence from manipulating response-code overlap. *Psychological Research*, *73*(3), 417–424. https://doi.org/10.1007/s00426-008-0152-8

Koch, I., Gade, M., Schuch, S., & Philipp, A. M. (2010). The role of inhibition in task switching: A review. *Psychonomic Bulletin & Review*, *17*(1), 1–14. https://doi.org/10.3758/PBR.17.1.1

Koch, I., Poljac, E., Müller, H., & Kiesel, A. (2018). Cognitive structure, flexibility, and plasticity in human multitasking-An integrative review of dual-task and task-switching research. *Psychological Bulletin*, *144*(6), 557–583. https://doi.org/10.1037/bul0000144

Koch, I., & Prinz, W. (2002). Process interference and code overlap in dual-task performance. *Journal of Experimental Psychology: Human Perception and Performance*, *28*(1), 192–201. https://doi.org/10.1037/0096-1523.28.1.192

Konishi, M., Berberian, B., de Gardelle, V., & Sackur, J. (2021). Multitasking costs on metacognition in a triple-task paradigm. *Psychonomic Bulletin & Review*, *28*(6), 2075–2084. https://doi.org/10.3758/s13423-021-01967-0

Konishi, M., Compain, C., Berberian, B., Sackur, J., & de Gardelle, V. (2020). Resilience of perceptual metacognition in a dual-task paradigm. *Psychonomic Bulletin & Review*, *27*(6), 1259–1268. https://doi.org/10.3758/s13423-020-01779-8

Kramer, A. F., Larish, J. F., & Strayer, D. L. (1995). Training for Attentional Control in Dual Task Settings: A Comparison of Young and Old Adults. *Journal of Experimental Psychology: Applied*, *1*(1), 50–76. https://doi.org/10.1037/1076-898X.1.1.50

Künzell, S., Broeker, L., Dignath, D., Ewolds, H., Raab, M., & Thomaschke, R. (2018). What is a task? An ideomotor perspective. *Psychological Research*, *82*(1), 4–11. https://doi.org/10.1007/s00426-017-0942-y

Laessoe, U., Hoeck, H. C., Simonsen, O., & Voigt, M. (2008). Residual attentional capacity amongst young and elderly during dual and triple task walking. *Human Movement Science*, *27*(3), 496–512. https://doi.org/10.1016/j.humov.2007.12.001

Liepelt, R., Fischer, R., Frensch, P. A., & Schubert, T. (2011). Practice-related reduction of dual-task costs under conditions of a manual-pedal response combination. *Journal of Cognitive Psychology*, *23*(1), 29–44. https://doi.org/10.1080/20445911.2011.448025

Liepelt, R., Strobach, T., Frensch, P., & Schubert, T. (2011). Improved intertask coordination after extensive dual-task practice. *Quarterly Journal of Experimental Psychology (2006)*, *64*(7), 1251–1272. https://doi.org/10.1080/17470218.2010.543284

Logan, G. D., & Gordon, R. D. (2001). Executive control of visual attention in dual-task situations. *Psychological Review*, *108*(2), 393–434. https://doi.org/10.1037//0033-295X.108.2.393

Maquestiaux, F., Ruthruff, E., Defer, A., & Ibrahime, S. (2018). Dual-task automatization: The key role of sensory-motor modality compatibility. *Attention, Perception & Psychophysics*, *80*(3), 752–772. https://doi.org/10.3758/s13414-017-1469-4

Meyer, D. E., & Kieras, D. E. (1997a). A computational theory of executive cognitive processes and multiple-task performance: Part 2. Accounts of psychological refractory-period phenomena. *Psychological Review*, *104*(4), 749.

Meyer, D. E., & Kieras, D. E. (1997b). A computational theory of executive cognitive processes and multiple-task performance: Part I. Basic mechanisms. *Psychological Review*, *104*(1), 3.

Miller, J., & Ulrich, R. (2008). Bimanual Response Grouping in Dual-Task Paradigms. *Quarterly Journal of Experimental Psychology*, *61*(7), 999–1019. https://doi.org/10.1080/17470210701434540

Monsell, S. (1996). Unsolved mysteries of the mind. In V. Bruce (Ed.), *Unsoved Mysteries of the Mind* (pp. 93–148). Erblaum (UK) Taylor&Francis.

Monsell, S. (2003). Task switching. *Trends in Cognitive Sciences*, *7*(3), 134–140. https://doi.org/10.1016/S1364-6613(03)00028-7

Naefgen, C., Caissie, A. F., & Janczyk, M. (2017). Stimulus-response links and the backward crosstalk effect—A comparison of forced- and free-choice tasks. *Acta Psychologica*, *177*, 23–29. https://doi.org/10.1016/j.actpsy.2017.03.010

Nett, T. (2017). *VoiceExperiment: This package allows the analysis of vocal responses to psychological experiments. R package version 1.0.2*.

Nijboer, M., Borst, J. P., van Rijn, H., & Taatgen, N. A. (2016). Driving and Multitasking: The Good, the Bad, and the Dangerous. *Frontiers in Psychology*, *7*. https://doi.org/10.3389/fpsyg.2016.01718

Norman, D. A., & Bobrow, D. G. (1975). On data-limited and resource-limited processes. *Cognitive Psychology*, *7*(1), 44–64. https://doi.org/10.1016/0010-0285(75)90004-3

Pashler, H. (1984). Processing stages in overlapping tasks: Evidence for a central bottleneck. *Journal of Experimental Psychology: Human Perception and Performance*, *10*(3), 358–377. https://doi.org/10.1037//0096-1523.10.3.358

Pashler, H. (1990). Do response modality effects support multiprocessor models of divided attention? *Journal of Experimental Psychology: Human Perception and Performance*, *16*(4), 826–842. https://doi.org/10.1037/0096-1523.16.4.826

Pashler, H. (1994). Dual-task interference in simple tasks: Data and theory. *Psychological Bulletin*, *116*(2), 220–244. https://doi.org/10.1037//0033-2909.116.2.220

Pashler, H., & Christian, C. L. (1994). *Bottlenecks in planning and producing vocal, manual and foot responses*. 61.

Pashler, H., & Sutherland, S. (1998). *The psychology of attention (Vol. 15)*. Cambridge, MA: MIT press.

Pieczykolan, A., & Huestegge, L. (2014). Oculomotor dominance in multitasking: Mechanisms of conflict resolution in cross-modal action. *Journal of Vision*, *14*(13), 1–17. https://doi.org/10.1167/14.13.18

Pisella, L., Arzi, M., & Rossetti, Y. (1998). The timing of color and location processing in the motor context. *Experimental Brain Research*, *121*(3), 270–276. https://doi.org/10.1007/s002210050460

Rinkenauer, G., Ulrich, R., & Wing, A. M. (2001). Brief bimanual force pulses: Correlations between the hands in force and time. *Journal of Experimental Psychology: Human Perception and Performance*, *27*(6), 1485–1497. https://doi.org/10.1037/0096-1523.27.6.1485

Ruthruff, E., Pashler, H., & Klaassen, A. (2001). Processing bottlenecks in dual-task performance: Structural limitation or strategic postponement? *Psychonomic Bulletin & Review*, *8*(1), 73–80. https://doi.org/10.3758/BF03196141

Salvucci, D. D., & Taatgen, N. A. (2010). *The Multitasking Mind*. Oxford University Press.

Sangals, J., Wilwer, M., & Sommer, W. (2007). Localizing practice effects in dual-task performance. *Quarterly Journal of Experimental Psychology*, *60*(6), 860–876. https://doi.org/10.1080/17470210600822720

Santiago-Espada, Y., Myer, R. R., Latorella, K. A., & Comstock Jr, J. R. (2011). *The multi-attribute task battery ii (matb-ii) software for human performance and workload research: A user's guide*.

Schuhfried, G. (1991). Wiener Determinationsgerät. *Grundprogramm Und Erweitertes Programm. Wiener Testsystem [Vienna Determination Test]. Dr. G. Schuhfried GmbH, Mödling*, 1–48.

Schumacher, E. H., & Hazeltine, E. (2016). Hierarchical Task Representation: Task Files and Response Selection. *Current Directions in Psychological Science*, *25*(6), 449–454. https://doi.org/10.1177/0963721416665085

Schumacher, E. H., Seymour, T. L., Glass, J. M., Fencsik, D. E., Lauber, E. J., Kieras, D. E., & Meyer, D. E. (2001). Virtually Perfect Time Sharing in Dual-Task Performance: Uncorking the Central Cognitive Bottleneck. *Psychological Science*, *12*(2), 101–108. https://doi.org/10.1111/1467-9280.00318

Shin, Y. K., Proctor, R. W., & Capaldi, E. J. (2010). A review of contemporary ideomotor theory. *Psychological Bulletin*, *136*(6), 943–974. https://doi.org/10.1037/a0020541

Stelzel, C., Schumacher, E. H., Schubert, T., & D'Esposito, M. (2006). The neural effect of stimulus-response modality compatibility on dual-task performance: An fMRI study. *Psychological Research*, *70*(6), 514–525. https://doi.org/10.1007/s00426-005-0013-7

Stephan, D. N., Josten, J., Friedgen, E., & Koch, I. (2021). Crossmodal Effects in Task Switching: Modality Compatibility with Vocal and Pedal Responses. *Journal of Cognition*, *4*(1), 9. https://doi.org/10.5334/joc.129

Stephan, D. N., & Koch, I. (2010). Central cross-talk in task switching: Evidence from manipulating input–output modality compatibility. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *36*(4), 1075–1081. https://doi.org/10.1037/a0019695

Stephan, D. N., Koch, I., Hendler, J., & Huestegge, L. (2013). Task Switching, Modality Compatibility, and the Supra-Modal Function of Eye Movements. *Experimental Psychology*, *60*(2), 90–99. https://doi.org/10.1027/1618-3169/a000175

Strayer, D. L., & Johnston, W. A. (2001). Driven to Distraction: Dual-Task Studies of Simulated Driving and Conversing on a Cellular Telephone. *Psychological Science*, *12*(6), 462–466. https://doi.org/10.1111/1467-9280.00386

Strobach, T., Frensch, P. A., Soutschek, A., & Schubert, T. (2012). Investigation on the improvement and transfer of dual-task coordination skills. *Psychological Research*, *76*(6), 794–811. https://doi.org/10.1007/s00426-011-0381-0

Strobach, T., Frensch, P., Müller, H., & Schubert, T. (2015). Evidence for the acquisition of dual-task coordination skills in older adults. *Acta Psychologica*, *160*, 104–116. https://doi.org/10.1016/j.actpsy.2015.07.006

Strobach, T., Hendrich, E., Kübler, S., Müller, H., & Schubert, T. (2018). Processing order in dual-task situations: The \textquotedblfirst-come, first-served\textquotedbl principle and the impact of task order instructions. *Attention, Perception & Psychophysics*, *80*(7), 1785–1803. https://doi.org/10.3758/s13414-018-1541-8

Strobach, T., & Schubert, T. (2017a). Mechanisms of Practice-Related Reductions of Dual-Task Interference with Simple Tasks: Data and Theory. *Advances in Cognitive Psychology*, *13*(1), 28–41. https://doi.org/10.5709/acp-0204-7

Strobach, T., & Schubert, T. (2017b). No evidence for task automatization after dual-task training in younger and older adults. *Psychology and Aging*, *32*(1), 28–41. https://doi.org/10.1037/pag0000144

Tombu, M., & Jolicøeur, P. (2003). A central capacity sharing model of dual-task performance. *Journal of Experimental Psychology: Human Perception and Performance*, *29*(1), 3–18. https://doi.org/10.1037/0096-1523.29.1.3

Tombu, M., & Jolicoeur, P. (2004). Virtually no evidence for virtually perfect time-sharing. *Journal of Experimental Psychology. Human Perception and Performance*, *30*(5), 795–810. https://doi.org/10.1037/0096-1523.30.5.795

Treisman, A. M., & Gelade, G. (1980). A feature-integration theory of attention. *Cognitive Psychology*, *12*(1), 97–136. https://doi.org/10.1016/0010-0285(80)90005-5

Watson, J. M., & Strayer, D. L. (2010). Supertaskers: Profiles in extraordinary multitasking ability. *Psychonomic Bulletin & Review*, *17*(4), 479–485. https://doi.org/10.3758/PBR.17.4.479

Wechsler, K., Drescher, U., Janouch, C., Haeger, M., Voelcker-Rehage, C., & Bock, O. (2018). Multitasking During Simulated Car Driving: A Comparison of Young and Older Persons. *Frontiers in Psychology*, *9*, 910. https://doi.org/10.3389/fpsyg.2018.00910

Welford, A. T. (1952). The Psychological refractory period and the timing of high-speed performance—A review and a theory. *British Journal of Psychology*, *43*(1), 2.

Wickens, C. D. (1981). *Processing Resources In Attention, Dual Task Performance, and Workload Assessment*. University of Illinois. https://apps.dtic.mil/dtic/tr/fulltext/u2/a102719.pdf

Wickens, C. D. (2008). Multiple resources and mental workload. *Human Factors*, *50*(3), 449–455. https://doi.org/10.1518/001872008X288394

Wühr, P., & Biebl, R. (2011). The role of working memory in spatial S-R correspondence effects. *Journal of Experimental Psychology: Human Perception and Performance*, *37*(2), 442–454. https://doi.org/10.1037/a0020563

Appendix

Table A1: *Triple-task costs, dual-task costs and standard deviation in milliseconds in comparison with single-tasks and triple-task costs and standard deviation in milliseconds in comparison with dual-tasks. Triple-tasks, dual-tasks, and single-tasks were always compared with the same stimulus (e.g., the color task in the triple-task with the color task in the single-task).*

Compared Stimulus	**Color**		**Location**		**Pitch**	
	Triple-task costs					
	M	*SD*	*M*	*SD*	*M*	*SD*
Difference to	Triple-Task					
Single-task	452	238	628	238	878	250
Location + color dual-task	86	132	80	132	-	-
Location + pitch dual-task	-	-	335	209	372	207
Color + pitch dual-task	83	176	-	-	217	211
	Location + color dual-task costs					
Difference to	Location + color dual-task					
Single-task	366	215	548	199	-	-
	Location + pitch dual-task costs					
Difference to	Location + pitch dual-task					
Single-task	-	-	293	198	506	180
	Color + pitch dual-task costs					
Difference to	Color + pitch dual-task					
Single-task	396	194	-	-	661	252

Contribution 2

Multi-tasking costs in triple-task performance despite dual-task preparation

Stefani, M., Sauter, M., & Mack, W. (under Review). Multi-tasking Costs in Triple-Task Performance Despite Dualtask Preparation. *Memory & Cognition*

Multi-tasking costs in triple-task performance despite dual-task preparation

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Abstract

This study explores the intricacies of multi-tasking by examining the effects of transitioning from dual-task to triple-task scenarios. Our research extends beyond conventional dual-task paradigms to investigate the impact of triple-task performance on two participant groups: those unprepared in single, dual, or triple tasks (N = 14) and those previously prepared in single and dual tasks (N = 13). The study consisted of a preparation phase with 9 sessions and an assessment phase with 8 sessions. In the assessment phase, both groups performed single, dual, and triple tasks of varying complexity (simple, medium, and complex). Despite the initial advantage observed in the prepared group, this advantage diminished throughout the sessions. Notably, both groups adopted distinct strategies for processing within the triple task, revealing the influence of task coordination on response times as the task set combinations expanded. The study demonstrates that training can facilitate applying skills acquired from specific tasks to others, with the formation of specific task pair sets playing a pivotal role in processing and coordination. Despite extensive training, the persistence of multi-tasking costs challenges traditional assumptions about eliminating such costs through practice. In conclusion, our research contributes to the current understanding of multi-tasking by highlighting the need for further exploration into inter(sub)task coordination and prioritization in multiple-task scenarios. The study underscores the complexities inherent in managing triple tasks and individuals' potential strategies. The findings suggest that ongoing refinement of cognitive models from dual tasks is necessary to accommodate the evolving nature of multi-tasking behaviors in more complex environments.

Keywords: dual task; triple task; task coordination; multitasking; training

Introduction

Imagine your first driving lesson: it was likely a blend of excitement and anxiety, with every action feeling uncoordinated and overwhelming. However, as you accumulated hours behind the wheel, your ability to navigate the vehicle improved dramatically. You learned to synchronize multiple tasks - braking, shifting gears, and monitoring traffic - all aimed at achieving a goal: traveling safely from point A to point B. Fundamentally, driving involves managing several tasks simultaneously to achieve one primary objective. But what if we shift the context from driving a car to riding a motorcycle? The skills required change, and so is how these skills are coordinated. Research in cognitive psychology, particularly in dual-task scenarios, shows that extended training can enhance our ability to juggle multiple tasks efficiently (Garner & Dux, 2023; Kramer et al., 1995; Liepelt et al., 2011; Schubert et al., 2017). This training leads to what is known as "transfer of learning". Transfer can be positive, where mastering one task aids in performing another, or negative, which hinders performance on subsequent tasks (for more about the taxonomy of the transfer, see Barnett & Ceci, 2002).

However, the dynamics of managing a goal become more complex the more tasks we introduce. A recent study by Stefani et al. (2022) explored this by examining behavior in triple-task scenarios, where participants had to manage three tasks simultaneously (visual-manual, visual-pedal, and auditory-vocal tasks). Unlike most dual-task studies that involve sequential processing of tasks, this study found that participants often grouped tasks (namely the visual-manual and visual-pedal tasks) to optimize performance. They endeavored to act correctly and efficiently while treating all tasks with equal priority. This approach to task grouping raises critical questions: Is this strategy a result of insufficient training employed to simplify the challenge of managing multiple tasks? Furthermore, can prior training in dual tasks enhance performance in triple-task scenarios? Our study builds on these inquiries, aiming to understand how training in dual-task scenarios might influence the management of more complex task combinations. We hope to uncover deeper insights into cognitive flexibility and task coordination by investigating these dynamics.

Dual-task training

Research has consistently shown that dual-task training, where individuals practice performing two tasks simultaneously, can significantly reduce response times (RTs) and error rates (Bherer et al., 2005, 2008; Hirst et al., 1980; Kramer et al., 1995; Liepelt et al., 2011; Ruthruff et al., 2003, 2006). This training effect is not confined to specific task types but extends across various cognitive domains, enhancing the general efficiency of task performance (Strobach, 2019; Strobach & Schubert, 2017a). Schumacher et al. (2001) demonstrated that with adequate training, participants could eliminate what is known as "dual-task costs" - the additional time and error typically associated with performing two tasks simultaneously compared to separately. In their study, participants engaged in concurrent visual-manual and auditory-vocal tasks, each requiring responses based on different sensory inputs. The tasks were presented simultaneously and had to be executed with equal priority. By comparing performance in dual-task to single-task conditions, Schumacher and colleagues found that participants could achieve *perfect time-sharing*, performing tasks together as efficiently as they did separately. Thus, multi-task costs refer to the performance decrement that occurs when an individual engages in multiple tasks simultaneously compared to when these tasks are performed separately. Zero dual-task costs or multi-task costs can be achieved, for example, by task automatization (Ruthruff et al., 2006; Schneider & Shiffrin, 1977), bypassing the central bottleneck (Maquestiaux et al., 2008, 2018; Ruthruff et al., 2001), or by shortening the response selection (Schubert et al., 2008) or other processing stages (Dux et al., 2009; Strobach et al., 2013), see also the review by Strobach and Schubert (2017) for a detailed discussion. Notably, the major improvements were primarily observed in the auditory task, suggesting that dual-task training may preferentially enhance certain types of task processing (Schumacher et al., 2001; Strobach et al., 2012, 2013; Tombu & Jolicoeur, 2004).

Reasons for improvement through training

One reason for such findings could be that the training may have enhanced the efficiency of response selection processes. Schubert and colleagues (2024) posit that working memory is crucial in the context of dual-task training, emphasizing that the initial setup of tasks in a dual-task scenario is fundamental to the benefits gained from such training. They propose three key hypotheses to validate the predictions of the Efficient Task Instantiation (ETI) model: firstly, dual-task coordination skills can be acquired through practice and successfully transferred to other situations; secondly, the development and execution of dual-task coordination skills are influenced by the complexity and difficulty of the individual tasks being performed simultaneously; thirdly, age-related declines in working memory capacity affect the ability to optimize and improve dual-task performance through practice (see also, Schubert & Strobach, 2018; Strobach et al., 2014). However, such improvements are subject to working memory capacity limitations (Schubert & Strobach, 2018), which involve storage, supervision, and coordination functions (Oberauer et al., 2000). As the number of tasks increases beyond two, the ability to coordinate them with the same efficiency is reduced. (Schubert & Strobach, 2018).

Another reason could be task automatization. Ruthruff et al. (2006) questioned whether the reduction of costs was possible either by integrating both tasks into one "super task" through task automatization or by shortening the processing stages. They trained participants in either an auditory-verbal task, a visual-manual task, or both, and all participants were later tested in a dual-task session. They concluded that processing bottlenecks could be mitigated by automatizing at least one task, mainly when tasks are compatible and straightforward. This implies that tasks combining visual-manual and auditory-vocal elements are less likely to interfere with each other compared to other combinations (see also Göthe et al., 2016). Maquestiaux et al. (2008, 2010) provided further evidence of task automatization in younger adults, and another study emphasized the critical role of sensorimotor compatibility in task automatization (Maquestiaux et al., 2018). Strobach and Schubert (2017) outlined five conditions necessary for optimal dual-task performance and potential task automation: 1) the task has to be instructed to be completed as fast as possible, 2) the compatibility of the tasks must be maintained, 3) extensive training must be provided, 4) both tasks must be given equal priority and 5) simultaneous processing of the stimuli must be possible (e.g., same onset asynchrony of 0 ms). Despite meeting these criteria, Strobach and Schubert (2017b) did not find evidence of task automation in young adults. It is important to note that their analysis was limited to dual-task trials with a specific sequence and did not encompass all possible trial permutations. This led them to conclude that post-training interference aligned more with capacity-limited processes rather than a shared capacity across tasks. However, as the ETI model indicates, improvements in response time may also be attributed to more effective task coordination.

Once participants are trained, task coordination becomes more efficient, and skills acquired in one task can often be applied to another. Liepelt et al. (2011) characterize intertask coordination (ITC) as a skill developed through extensive dual-task practice that could then be generalized across various dual-task scenarios. They showed that participants in a 'hybrid' group - who trained on both single and dual tasks - did not experience significant difficulties when the tasks were varied and consistently outperformed those who trained solely on single tasks. Consequently, they suggested that the ITC may be independent of the single tasks itself; the ITC poses additional demands. However, it is also important to note that the improvements were explicitly observed in auditory tasks, which were always executed subsequent to the visual tasks, and this applied only when one of the dual-task components was changed (see also Bherer et al., 2008). Expanding on this, Strobach et al. (2012) investigated whether skill transfer was possible when both tasks were changed, discovering that no differences emerged between groups under these conditions. Strobach et al. (2013) continued this approach by using the transfer effects to determine after which amount of time dual-task practice leads to an improvement. They concluded that enhancement likely results from reduced time required for central response selection and perceptual processing in the auditory task, providing further evidence for the ETI model (see also Strobach & Schubert, 2017).

The previous triple-task study

In a previous study, Stefani et al. (2022) investigated participants' performance in a triple-task paradigm over three sessions, which included single, dual, and triple tasks presented in mixed blocks. Two of the three tasks (visual-manual and auditory-pedal) were adopted from the experimental design of Schumacher et al. (2001), but in the tiple-task study, all task types were presented in a mixed block. Thus, a single-task block contained all single tasks, a dual-task mixed block contained all single and dual tasks, and a tripe-task mixed block contained single-, dual-, and triple tasks. Stefani et al. (2022) observed two notable findings. Firstly, response times increased substantially in triple tasks compared to dual and single tasks. In mixed blocks, single-task response times ranged from 689 ms to 971 ms, which was slower than those reported in dual-task studies with a mixed block design (see Bherer et al., 2008; Strobach & Schubert, 2017). However, direct comparisons between these studies should be made with caution due to differences in experimental designs and task complexity. Secondly, Stefani et al. (2022) observed that participants often executed the two visual tasks requiring hand and foot responses within a tight time frame (difference ≤ 100 ms), suggesting a grouping strategy to optimize task completion. Stefani et al. (2022) assumed that interference between the two visual tasks might be limited due to either (weak) crosstalk, as discussed by Koch (2009), or a bottleneck within the visual system, a concept supported within the dual-task framework by Tombu & Jolicœur (2003) and Wickens (1981). This interference arises because both tasks compete for similar visual processing resources, leading to potential delays or reduced efficiency in task execution.

Efforts to apply the response selection bottleneck (Pashler, 1984) or the EPIC model (Meyer & Kieras, 1997a, 1997b) to predict outcomes in triple-task studies encounter limitations. Specifically, the bottleneck model for response selection overlooks strategic or cognitive components, which are crucial for understanding complex task management. While the EPIC model incorporates strategic aspects, workload, training, and compatibility, it still falls short in providing detailed explanations for the findings of Stefani et al. (2022).

Instead, in Stefani et al. (2022), it appears that participants may have adopted a strategy of delaying their responses until both responses to the visual subtasks were prepared, resulting in nearly simultaneous execution. This raises the question of whether extensive training in triple tasks across multiple sessions would further modify or reinforce this response grouping behavior. Additionally, it is worth investigating the potential effects of prior dual-task training on triple-task performance. Participants who have already mastered dual tasks may exhibit an advantage and demonstrate different performance patterns when faced with triple tasks compared to those without prior training.

The current triple-task study

Initially, we established a group of participants trained in dual tasks as a *prepared group*, utilizing visual-manual and auditory-vocal tasks with zero stimulus onset asynchrony (SOA) in a mixed-block format using two-choice response alternatives. Over seven experimental sessions, all tasks remained the same. We referred to this training as the *preparation phase*. Aligned with Strobach and Schubert's (2017b) criteria for optimal dual-task performance, we anticipated that the prepared group would achieve seamless task integration, or '*perfect time-sharing*', akin to the performance in single tasks (Schumacher et al., 2001; for a discussion about perfect time-sharing see Tombu & Jolicoeur, 2004). Following the *preparation phase*, we introduced a third task during the subsequent *assessment phase*. This visual-pedal task, activated by foot pedals, was added to the established dual task, creating a triple-task scenario. The *assessment phase* was performed by both the *prepared group* from the *preparation phase* and a new *unprepared group* without prior dual-task training.

Based on the ETI model, even if it does not make any direct statements about differences between trained and untrained individuals, we expected the prepared group, who had received dual-task training during the preparation phase, to perform the triple task more efficiently, with quicker responses and fewer errors than the unprepared group, who had not received prior training (Liepelt et al., 2011; Schubert & Strobach, 2018). The training advantage observed in the prepared group arises from transfer effects through intertask coordination, which is independent of the component tasks trained beforehand, even when considering the addition of new tasks (Liepelt et al., 2011; Schubert et al., 2017; Schubert & Strobach, 2018; Strobach et al., 2012). However, even with extensive training, we hypothesized that perfect time-sharing across all three tasks would not be feasible. This is due to the overlapping stimulus-response (S-R) mappings in the two visual tasks (Hazeltine et al., 2006; Ruthruff et al., 2001; Sommer et al., 2001; Stefani et al., 2022) and the increased demands on task coordination and working memory (Schubert & Strobach, 2018).

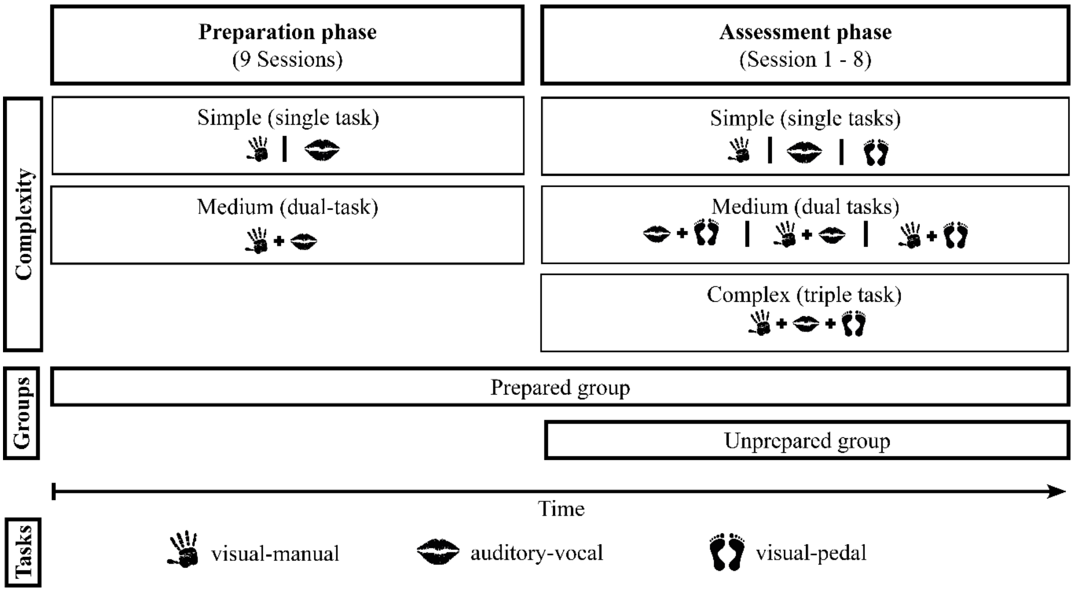
Methods

Participants

In the preparation and assessment phase, 13 students (4 females and 9 males, *M* = 22.5, SD = 2.8) participated as a prepared group, see **Figure 1**. In the assessment phase, 14 students (5 females and 9 males, *M* = 22.1, SD = 1.7) participated as an unprepared group. Another nine participants used their right to withdraw after the preparation phase[1], and four from the unprepared group during the assessment phase. Conducting a power analysis with G*Power for our repeated measures ANOVA, we aimed for a significance level (α) of 0.05 and a statistical power (1−β) exceeding 0.9 (Faul et al., 2009). Guided by prior studies (Liepelt et al., 2011; Schubert et al., 2017; Strobach et al., 2012), we chose an effect size *F* of 0.33 considering the within-between interaction across 9 sessions, each comprising 3 tasks (visual-manual, visual-pedal, auditory-vocal) with varying complexities (simple, medium, complex), the analysis revealed that a sample size of 6 participants in each group is necessary to meet these criteria. Participants attended up to 9 sessions during the preparation phase and 8 in the assessment phase, each lasting approximately 1 hour and scheduled at least one day apart. Combining all the sessions completed by the two groups results in a cumulative experimentation time of 333 hours. All participants had normal or corrected-to-normal vision and no hearing impairments. They provided informed consent and were given course credit or money per hour attended as compensation for their participation. All procedures performed in this study were accepted by the ethical committee of the University of the Bundeswehr Munich and in accordance with the 1964 Helsinki Declaration.

Figure 1

Design of the study with its phases, task complexities, and groups without the block condition



Note. It was investigated whether prepared subjects' prior knowledge of two simple and one medium task coordination complexity (preparation phase) resulted in an advantage through transfer effects. One group (prepared group) trained across nine sessions to generate prior knowledge. In the assessment phase, which now consisted of three complexities of tasks (simple, medium, and complex), another group (unprepared group) was added without prior knowledge.

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[1] Participants were informed at the beginning that they would be taking part in two phases running over two semesters. However, some exercised their right not to continue participating and did not participate in the assessment phase in the second semester. No exclusion was made by the test administration.

Setup

The experiment was programmed in MatLab® 2017a with the Psychtoolbox-3.013 (Brainard et al., 2016) on a PC running Linux OS® with Ubuntu 18.04 LTS. For recruitment, we used the software ORSEE (Greiner, 2015). The study was conducted in noise-reduced medium-lit cabins. The visual stimuli were displayed on an EIZO® color monitor with a screen diagonal of 27 inches and a frame rate of 144 Hz at a resolution of 2560x1440 pixels. The BlackBox® toolkit response pad with a voice key feature was used to capture the response time of the manual and the vocal responses. The visual task was completed with the index and middle finger of the dominant hand (determined by the Edinburgh Handedness Inventory (Oldfield, 1971)) via two adjacent keys on the response pad. The Sennheiser® Model PC3 headset was used to record the voice and reproduce the auditory stimuli.

Task

Participants performed three tasks according to three levels of complexity. Complexity is described here as coordinative complexity, defined by the amount of coordinative processing required to control and monitor the flow of information between interconnected processing steps (Mayr & Kliegl, 1993). We distinguish between simple (the three single-tasks), medium (the three dual-tasks), and complex (the triple-task) tasks, whereas all single tasks (or all sub-tasks in the dual and triple tasks) were based on two-choice response time alternatives. The tasks were a visual-manual (VM task), an auditory-vocal task (AV task), and a visual-pedal task (VP task), see **Figure 2**. Each task was generally structured as follows: first, participants were presented with a fixation screen for 500, 1000, or 1500 ms with a fixation cross in the center (1° diameter) of the screen and, in the preparation phase, two horizontal dashes, in the assessment phase, three horizontal dashes (5° width 5 pixels high) positioned slightly below of the centers of the circles as a placeholder. The stimulus remained for 100 ms, and the trial ended when the participant responded. After the response, the trial ended with the presentation of the response time for 700 ms.

Figure 2

Description of the multi-tasking tasks

Note. In the visual-manual task, the participants had to differentiate between right and left by pressing an assigned button; in the auditory-verbal task, between a high and low tone by a verbal response (high or low); and in the visual-pedal task, between green and red by pressing a button with their feet on assigned pedals.

In the VM task, participants responded manually to a white circle (2.5° radius) appearing randomly and equally distributed at the left or right position (each at 9.0° distance from the middle) arranged horizontally on the screen by pressing a button (left position with the index finger and right position with the middle finger). In the AV task, participants responded vocally via the voice key when hearing a sine wave tone at frequencies of either 350 or 1650 Hz by saying "LOW" or "HIGH" (German: "TIEF" or "HOCH"). In the VP task, participants responded with foot pedals discriminating between red (RGB: 255,0,0, left foot) and green (RGB: 0,0,255, right foot), which colored the white circle.

A single-task, dual-task, or triple-task could be presented as a function of session and block condition. Thus, participants performed pure single-task blocks, mixed dual-task blocks (consisting of single and dual tasks), and mixed triple-task blocks (consisting of single, dual, and triple tasks). Single tasks had a simple complexity level, dual tasks had a medium complexity level, and triple-task complexity level was complex. The dual-task could be a VM-AV, VM-VP, or VP-AV task. The triple-task consisted of all three tasks.

In the dual-tasks and the triple-task, participants had to respond to all two or three tasks as fast as possible (tasks presented with an SOA of 0 ms).

Design

The experiment was structured in two main phases. Initially, a subset of participants underwent training during the *preparation phase*, where they were exposed to simple and medium complexity tasks, thereby achieving the status of prepared participants. Subsequently, in the *assessment phase*, both the prepared participants (from the preparation phase) and unprepared participants (who had no prior exposure to the tasks) received training.

Preparation phase. In each session, participants had to perform three different types of experimental blocks. Two blocks were pure single-task blocks, respectively, with only VM or AV single-tasks, and the third block was a mixed dual-task block with both single-tasks and dual-tasks. Each session always started with two pure single-task blocks, alternating two mixed dual-task blocks and one of the two pure single-task blocks. In a pre-session, each participant passed through each of the three possible blocks to become familiar with the tasks (the pre-session was not included in the results). In session 1, eight mixed dual-task blocks and six pure single-task blocks were completed. Two additional mixed dual-task blocks had to be performed from the second session onwards. Each pure single-task block consists of 24 single-task trials, and each mixed dual-task block consists of twelve AV single-tasks, twelve VM single-tasks, and 28 VM-AV dual-tasks.

Assessment phase. In eight training sessions, participants had to perform five different types of experimental blocks. The first three experimental blocks comprised three pure single-task blocks with only one of the three single-tasks each, the fourth experimental block comprised one mixed dual-task block with all three single-tasks and three dual-tasks combinations, and the fifth experimental block comprised one mixed triple-task block with all single-tasks, dual-tasks, and the triple-task. In each session, three single-task blocks were followed by two mixed dual-task blocks, two mixed triple-task blocks, one mixed dual-task block, and one mixed triple-task block. Each single-task block consists of twelve single-task trials, each dual-task mixed block consists of eight tasks for every single-task and twelve tasks for each dual-task, and each triple-task block has, in addition to the tasks from the dual-task block, 24 triple-tasks.

Participants were instructed to perform all the tasks as quickly and accurately as possible. They were told not to respond in a particular order and to prioritize all tasks equally.

Analyses

Verbal responses were analyzed when the voice key was triggered using the R-Package "VoiceExperiment" (Nett, 2017). For uncertain audio analysis results, trials were listened to and classified manually. RStudio 2023.06.1 (RStudio Team, 2016) and R 4.3.1 were used with the tidyverse package version 1.3.0 (Wickham, 2017) for data preparation and creating figures and JASP version 0.17.3 to calculate repeated measure ANOVAs and post hoc analyses. We calculated mean response times and error rates per participant and condition if not stated otherwise. Post hoc tests were conducted on the estimated marginal means with Bonferroni's *t*-test, and we used the Bonferroni equation for computing degrees of freedom.

Transparency and openness

We report how we determined our sample size, all data exclusions (if any), all manipulations, and all measures in the study. All data, analysis code, and research materials are available at https://osf.io/fr4wa/?view_only=f3110a5833a84f18b5486ec449dfde1c. This study's design and its analysis were not pre-registered.

Results

Inclusion and Exclusion of Data

Trials with response times below 80 ms and above 4500 ms were removed (*preparation phase*: simple tasks: 1.2 % and medium tasks: 1.0 %; *assessment phase:* simple tasks: 1.1 %, medium tasks: 0.9 %, and complex tasks: 1.0 %). These RTs came about when participants spoke too softly (RT > 4500 ms) or made noises during the task (RT < 80 ms). Only correct trials were included in the response time analyses. This means that all (sub)tasks had to be executed correctly.

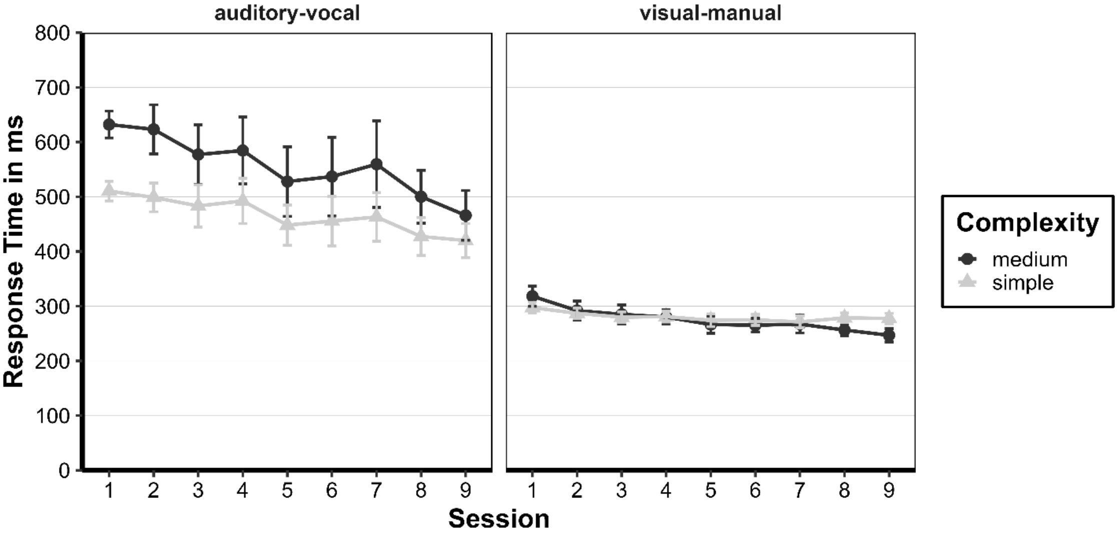
Preparation Phase

The preparation phase served to train participants on performing the visual-manual and auditory-vocal tasks concurrently as a dual task. Since the training process itself was not the primary focus, details related to the training are provided in the appendix. This section analyzes only the final session 9 of the preparation phase to establish the baseline performance level of the prepared participants before proceeding to the assessment phase.

RT - Last session. To describe their status after 9 sessions of preparation, a repeated measures ANOVA with Greenhouse-Geisser corrections for violations of sphericity was performed with the within-subject factors complexity (simple and medium) and task (visual-manual and auditive-vocal) for session 9. The main effect of complexity was not significant, $F(1, 12) = 0.53$, $p = .48$, $\eta^2p = 0.042$. The main effect of the task was significant, $F(1, 12) = 37.9$, $p < .001$, $\eta^2p = 0.759$. Participants responded faster to the visual-manual task ($M = 262$ ms) than to the auditive-vocal task ($M = 443$ ms). The interaction between task and complexity was significant, $F(1, 12) = 17.48$, $p = .001$, $\eta^2p = 0.593$, see **Figure *3***. The complexity level of the visual-manual task did not differ (*M* = -31 ms, 95% CI [-71 ms; 10ms], p_{bonf} = .229), but the complexity level of the auditive-vocal task (*M* = 46 ms, 95% CI [6 ms; 86 ms], p_{bonf} = .019).

Figure 3

Response times for all sessions of the preparation phase

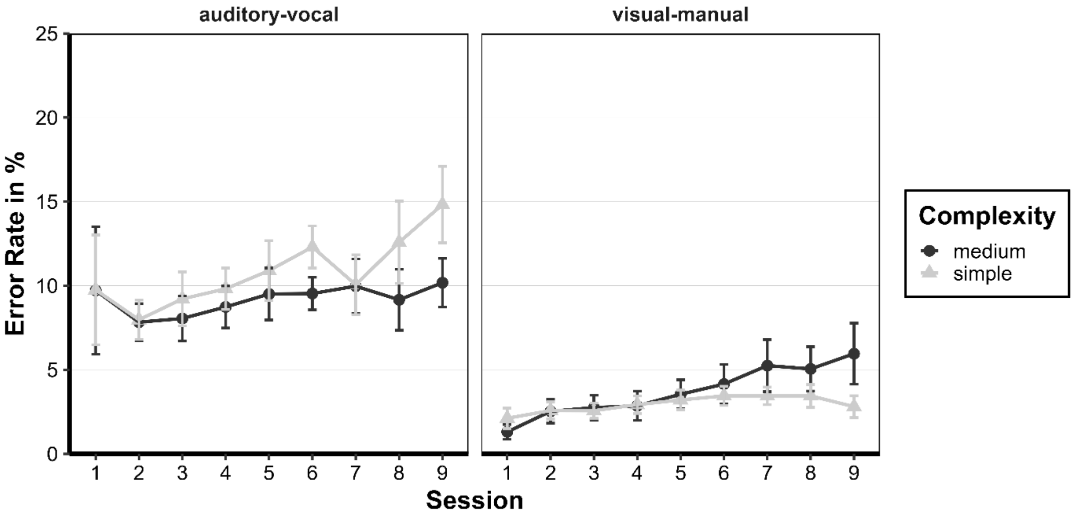


Note. Mean response times of the preparation phase of the prepared group in ms (calculated from individual participant's means) as a function of complexity (simple or medium), task (auditory-vocal or visual-manual), and session (1 – 9). Error bars represent the +/-1 standard error of the mean.

ER - Last session. To assess participants' status after 9 preparation sessions, a repeated measures ANOVA with Greenhouse-Geisser corrections for violations of sphericity was used, similar to the response times. The main effects for complexity, $F(1, 12) = 9.7$, $p = .009$, η^2p = 0.447, and task, $F(1, 12) = 34.95$, $p < .001$, η^2p = 0.744, as well as the interaction between complexity and task, $F(1, 12) = 25.33$, $p < .001$, η^2p = 0.679, were significant. The complexity simple and medium were significantly different (*M* = 4.6 %, 95% CI [1.4 %; 7.8 %], p_{bonf} = .009), and participants made fewer errors in the VM task than the AV task (*M* = 6.5 %, 95% CI [4.1 %; 8.9 %], p_{bonf} < .001) but this difference was only observed in the complexity simple (*M* = 12.5 %, 95% CI [7.8 %; 17.2 %], p_{bonf} < .001).

Figure 4

Error rates for all sessions of the preparation phase



Note. Mean error rates of the preparation phase of the prepared group in percentage (%) (calculated from individual participant's means) as a function of complexity (simple or medium), task (auditory-vocal or visual-manual), and session (1 – 9). Error bars represent the +/-1 standard error of the mean.

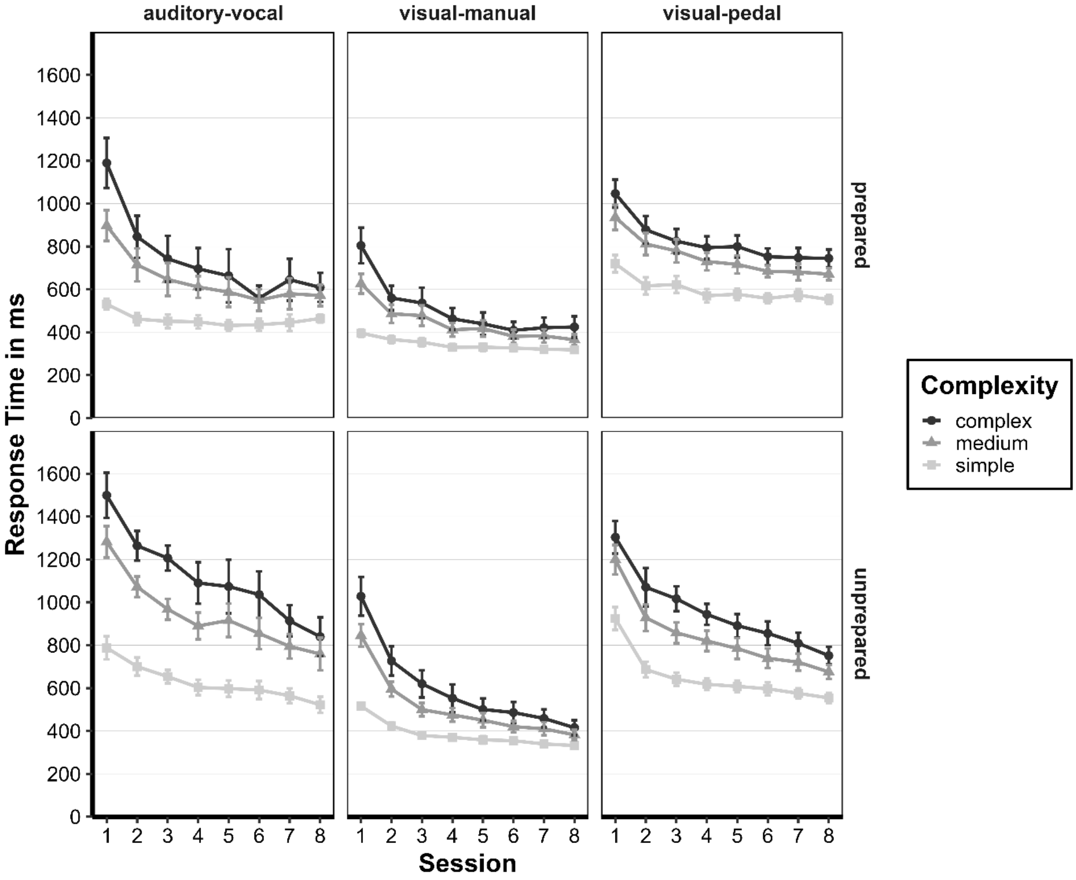
Assessment Phase

This section delves into the key findings observed between the two preparation groups across different levels of task complexity and their sessions. The analysis aims to unravel three pivotal questions. Initially, the investigation seeks to determine if the group that underwent dual-task training exhibits a performance advantage over the unprepared group, especially in the first session. Subsequently, a particular point of interest was whether participants tended to group the two visual tasks together in the last session after training, mirroring the pattern observed in a preceding study involving a triple-task scenario. Lastly, the analysis addresses the persistence of multi-task costs in the last session. Despite the anticipated improvements from dual-task training, it is imperative to identify and quantify any residual challenges participants face when juggling multiple tasks. An analysis of the training process can be found in the appendix.

RT - First session. We calculated a repeated measure ANOVA with Greenhouse-Geisser corrections for violations of sphericity with the within-subject factors complexity (simple, medium, and complex), and task (visual-manual (VM), visual-pedal (VP), and auditory-vocal (AV)) and between-subject factor preparation status (prepared and unprepared) for the session 1, see also **Figure 5**. The main effect for the preparation status was significant, $F(1, 25) = 9.98$, $p = .004$, $\eta^2p=.285$. The prepared group had $M = 239$ ms, 95% CI [84ms; 396 ms], and responded faster than the unprepared group. Participants needed for the complexity complex ($M = 1150$ ms) more time than for medium ($M = 948$ ms) and for medium more time than for simple ($M = 691$ ms), $F(1.21, 30.27) = 156.60$, $p < .001$, $\eta^2p=.862$ and was fastest in the VM task ($M = 702$ ms) with no differences between the VP ($M = 1042$ ms) and AV task ($M = 1045$ ms), $F(1.84, 45.90) = 49.26$, $p < .001$, $\eta^2p=.663$. The interaction between complexity and task was also significant, $F(2.34, 58.61) = 20.19$, $p < .001$, η^2p=.447, whereas participants responded in complexity simple with VM (M = 486 ms) → AV (M = 685 ms) → VP (M = 889 ms) but differently in medium VM (M = 689 ms) → VP (M = 1048 ms) → AV (M = 1093 ms) and complex VM (M = 916 ms) → VP (M = 1175 ms) → AV (M = 1344 ms). The interaction between task and preparation status, $F(1.84, 45.90) = 1.90$, $p = .165$, η^2p=.071, and complexity, task, and preparation status was not significant, $F(2.34, 58.61) = 0.51$, $p = .631$, $\eta^2p = .020$.

Figure 5

Response times for all sessions of the assessment phase



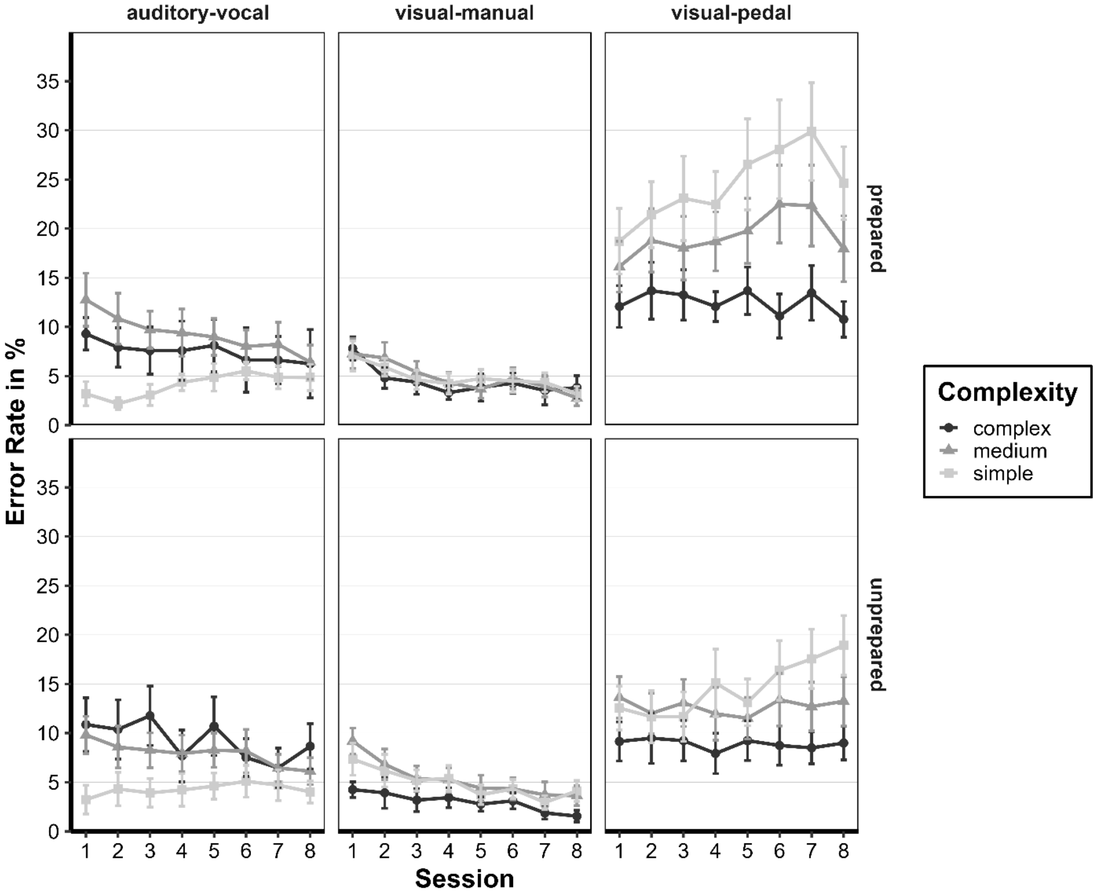
Note. Mean response times of the assessment phase of the prepared and unprepared group in ms (calculated from individual participant's means) as a function of complexity (simple, medium, or complex), task (auditory-vocal, visual-manual, visual-pedal), and session (1 – 8). Error bars represent the +/-1 standard error of the mean.

ER - First session. We conducted the same repeated measure ANOVA with Greenhouse-Geisser corrections for violations of sphericity for the error rate, similar to the response times; see **Figure 6.** The preparation status's main effect was insignificant, $F(1, 28) = 0.63$, $p = .433$, $\eta^2p < .001$. The main effects for complexity, $F(1.98, 55.50) = 11.03$, $p < .001$, $\eta^2p < .001$, and for task, $F(1.46, 40.96) = 14.51$, $p < .001$, $\eta^2p < .001$, were significant. The interaction between complexity and task was also significant, $F(3.08, 86.36) = 15.60$, $p < .001$, $\eta^2p < .001$, whereas participants made different errors dependent on complexity; simple: AV

(*M* = 3.1 %) → VM (*M* = 7.1 %) →VP (*M* = 15.5 %) but differently in medium: VM (*M* = 8.122 %) → AV (*M* = 11.180 %) → VP (*M* = 14.782 %) and complex: VM (*M* = 5.918 %) → AV (*M* = 9.975 %) → VP (*M* = 10.506 %). No interaction between task and preparation status, *F*(1.46, 40.96) = 1.13, *p* = .316, η^2p < .001. Significant interaction with complexity, task, and preparation status, *F*(3.08, 86.36) = 3.23, *p* = .025, η^2p < .001. The interaction effect is based on the differences in the AV task, with the prepared group producing the most errors in the complexity medium (*M* = 12.8%) and the unprepared group in the complexity complex (*M* = 10.9%).

Figure 6

Error rates for all sessions of the assessment phase

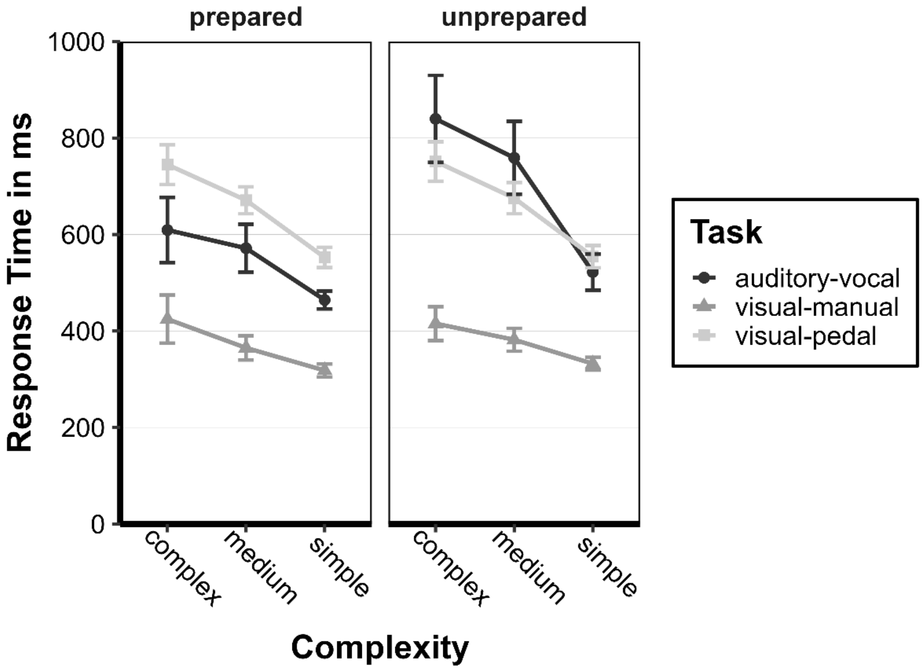


Note. Error rates of the assessment phase of the prepared and unprepared group in ms (calculated from individual participant's means) as a function of complexity (simple, medium, or complex), task (auditory-vocal, visual-manual, visual-pedal), and session (1 – 8). Error bars represent the +/-1 standard error of the mean.

RT – Last session. For the last session in the assessment phase, we calculated a repeated measure ANOVA with Greenhouse-Geisser corrections for violations of sphericity with the within-subject factors complexity (simple, medium, and complex) and task (visual-manual (VM), visual-pedal (VP), and auditory-vocal (AV)) and between-subject factor preparation status (unprepared and prepared) for the last session; see also **Figure 7**. We observed no significant differences between the unprepared and prepared groups F(1, 25) = 1.31, p = .262, η^2p = 0.050, but descriptively a difference of 55 ms 95% CI [-153 ms; 44 ms] could still be observed ($M_{prepared}$ = 535 ms, $M_{unprepared}$ = 590 ms). However, the analysis of the individual tasks across all sessions revealed a significant difference in the main effect for the auditory-vocal task, see **Table 4** in the appendix. Furthermore, independent of the preparation status (interaction between complexity and preparation status, F(1.10, 27.56) = 0.97, p = .341, η^2p = 0.038), both groups required more time to perform the tasks with increasing complexity (main effect for complexity, F(1.10, 27.56) = 38.02, p < .001, η^2p = 0.603). Post hoc tests showed significant differences between all levels of complexity (ps < .002): complex (M = 631 ms) > medium (M = 571 ms) > simple (M = 487 ms). Furthermore, VM (M = 381 ms) was generally performed faster than VP (M = 681 ms) or AV (M = 626 ms). However, there was no difference between VP and AV (the main effect of the task, F(1.49, 37.25) = 69.48, p < .001, η^2p = 0.735). The interaction of task and preparation status, F(1.49, 37.25) = 5.68, p = .012, η^2p = 0.185, further showed that prepared participants favored VM (M = 376 ms) to AV (M = 546 ms) and AV to VP (M = 684 ms) and the unprepared VM (M = 386 ms) to VP (M = 678 ms) to AV (M = 706 ms) in order to process the tasks. However, AV and VP response times were not significantly different within the two groups. It did indicate, however, that prepared participants preferred the previously trained tasks (VM and AV). The difference in response times of responding to VP and AV differed between the two groups, which was evident in the interaction effects of complexity and task, F(1.97, 49.18) = 16.23, p < .001, η^2p = 0.394, as well as in complexity, task, and preparation status, F(1.97, 49.18) = 4.12, p = .023, η^2p = 0.141. Across all complexities, there was no significant difference in any of the groups between VP and AV, except in the prepared group when the tasks were simple, M = 172 ms, 95% CI [43 ms; 335 ms]. Descriptively, however, a difference of M = -135 ms, 95% CI [-299 ms; 28 ms] could be observed in the complexity complex between AV and VP in the prepared group and M = 88 ms, 95% CI [-69 ms; 246 ms] in the unprepared group. For a better overview of the differences between the subtasks (inter-response intervals) in the complexity complex, see **Table 1**.

Figure 7

Response times of the prepared and unprepared group in the last session of the assessment phase



Note. Mean response times for the last session (last session of the assessment phase) in ms (calculated from individual participant's means) for the prepared and unprepared group as a function of complexity (simple, medium, or complex) and task (auditory-vocal, visual-manual, or visual-pedal). Error bars represent the +/-1 standard error of the mean.

Table 1

Inter-Response-Interval in the last session of the assessment phase

	prepared		unprepared	
Task 1 – Task 2	*M*	*95% CI*	*M*	*95% CI*
VM – AV	185	[21; 348]	424	[267; 582]
VM – VP	320	[157; 484]	336	[178; 494]
VP – AV	135	[-28; 299]	88	[216; 559]

Note. Mean differences of response times of the complex sub-tasks in ms for the last session (calculated from individual participant's means) for the prepared and unprepared group. Values were constantly reported to be positive. Tasks were visual-manual (VM), auditory-vocal (AV), and visual-pedal (VP).

ER – Last session. We calculated the same repeated measure ANOVA with Greenhouse-Geisser corrections for violations of sphericity for the error rate for the last session. We observed no significant differences between the two groups, $F(1,25) = 0.302$, $p = .587$, $\eta^2p = 0.012$. Furthermore, no interaction with the factor preparation status was significant, complexity and preparation status, $F(1.65, 41.15) = 0.11$, $p = .861$, $\eta^2p = 0.004$; task and preparation status, *F*(1.37, 34.22) = 0.81, $p = .411$, $\eta^2p = 0.031$; complexity, task and preparation status, *F*(2.84, 71.05) = 1.25, $p = .297$, $\eta^2p = 0.048$. The main effects for complexity, *F*(1.65, 41.15) = 9.20, $p = .001$, $\eta^2p = 0.269$, and task, *F*(1.37, 34.22) = 33.12, $p < .001$, $\eta^2p = 0.570$, were significant as well as the interaction between complexity and task, *F*(2.84, 71.05) = 15.41, $p < .001$, $\eta^2p = 0.381$. Most errors occurred in the simple tasks (10.1 %), followed by medium (8.6 %) and complex tasks (6.5 %). In the VP task, the most errors were observed across all complexities (16.0 %), followed by the AV task (6.0 %) and VM task (3.2 %). Interestingly, participants made significantly fewer errors in the VP task with rising complexity (21.9 % → 16.2 % → 10.0 %; *ps* < .001), unlike the other two tasks, where the error rates remained statistically constant across the complexity.

Discussion

The majority of multi-tasking research is based on dual-task paradigms. Nevertheless, we argue that refining the current models requires extensions to scenarios with more than two concurrent tasks. The present study builds on the premise that triple-task performance is systematically distinct from dual-task performance (Stefani et al., 2022). We examined the impact of a triple-task scenario on two participant groups: one with no prior preparation and another who had previously prepared (trained) on two of the three tasks involved in the form of single and dual tasks.

Assessment of Preparation Benefits

We initially hypothesized that participants could gain an advantage by training/ preparation part of the upcoming triple task beforehand. The expectation was that this preparation would enhance performance on the familiar tasks and the subsequent unfamiliar tasks. While the first seems logical at first glance, it is not immediately logical on closer inspection. The two tasks were precisely the same, but in the *assessment phase*, they occurred in a different setting, i.e., the possible response combinations increased rapidly with the third task (triple-task mixed blocks consisted of the three single tasks, three dual tasks, and the triple task). During the preparation phase, participants had to manage two possible task sets with three possible combinations: two single tasks and one dual task. Introducing the third task more than doubled the task set combinations to seven. One group underwent training with both the visual-manual and auditory-vocal tasks to evaluate the impact of preparation. This training led to notable improvements in the visual-manual task, where participants managed to perform without incurring additional time costs (*M* = -31 ms). In contrast, the auditory-vocal task continued to present a response delay (*M* = 46 ms). This means that contrary to other training studies, statistically, interference could only be reduced in the visual-manual task at the end of session 7 in the *preparation phase*. For the auditory-vocal task (complexity medium vs. simple), a difference of 46 ms could still be observed. This partial improvement aligns with findings from Liepelt et al. (2011), where participants also showed enhancements in only one of the dual tasks. However, the results of Lyphout-Spitz et al. (2024) showed that the central bottleneck could be bypassed even if costs can still be observed. Lyphout-Spitz et al. found evidence that people can perform two novel tasks in parallel without a central bottleneck, contradicting prevailing theories, if they are properly prepared - especially by boosting preparation for the second task through intermixing single-task trials. Nearly half the participants were able to bypass the central bottleneck when preparation for the second task was boosted in this way.

Furthermore, compared with Schumacher et al. (2001) and Liepelt et al. (2011), we observed significantly higher error rates. The error rates in the dual-tasks (complexity medium) were almost twice as high as in Schumacher et al. (2001) and Liepelt et al. (2011). However, the methodological structure differs in two essential factors: it was only necessary to differentiate between two and not three possible answers in the present experiment, and the participants received no reward (money in any way) for each correct answer. Possibly, first, the combination of fewer choices; second, the instruction to be as fast as possible (but also to answer as correctly as possible); and third, the response time feedback after each trial led to an increased number of wrong answers which may be the result of trading off speed and accuracy in favor of speed. However, only the training status was relevant to our further research question. While the *preparation phase* offered some expected benefits, the complexities introduced by adding a third task reveal a deeper layer of interaction between task performance and cognitive coordination.

Impact of Task Complexity on Coordination and Performance

The intricacies of task coordination become even more pronounced as we consider the role of task complexity on performance, where subtle differences in coordination strategies emerge. In particular, both groups coordinated the three subtasks within the triple task slightly differently (which could only be observed descriptively in the inter-response intervals; see Table 1). Previous observations by Stefani et al. (2022) indicated that participants tended to synchronize their responses to both visual tasks, responding to them in a closely matched timeframe. However, these findings were based on shorter training durations where random variation could have influenced the results. In contrast, our study, which involved more extensive training, did not confirm this pattern of synchronized responses. Instead, we found that the trained participants' response patterns varied depending on their prior training experience.

We had anticipated that the most effective coordination strategy, or Intertask Coordination (ITC), would involve standard pairings of modality-specific features within the triple task, as these pairings could be processed more efficiently and rapidly, as Göthe et al. (2016) suggested. Nonetheless, the actual behavior of participants diverged from this expectation. Those with dual-task training tended to complete the familiar tasks first before addressing the third, newly introduced task. Consequently, the trained and untrained groups developed distinct ITC strategies based on their experience. Moreover, the variety of task set combinations provided appeared to impact ITC. We noted performance variances across tasks of differing complexity, and the simple tasks elicited slower response times than those reported in dual-task research. This disparity could be attributed to our study's broader range of task combinations.

De Jong (1995) and Gottsdanker (1979) have already investigated the difference between homogeneous (only one task set occurs) and mixed blocks (multiple task sets). Both found significant differences between the two blocks. Participants prepared for a particular task and then responded faster to that task than when another task was required. However, Tombu and Jolicoeur (2004) doubted whether the effect could be generalized, as Schumacher et al. (2001; see also Strobach et al., 2013) did not observe any differences between single tasks in homogeneous and mixed blocks. Despite this, similar to De Jong (1995) and Gottsdanker (1979), we observed significant differences in descriptives compared to mixed blocks with these studies. In homogeneous blocks, participants can focus on a single task set, which is the mental configuration required to execute a specific task, including relevant sensory information, responses, and cognitive processes. In contrast, mixed blocks involve multiple task set combinations, requiring participants to switch between them. This switching process incurs a "switch cost" regarding increased response time and decreased accuracy due to the need for additional cognitive processes to reconfigure the mental state for the next task (Mayr & Kliegl, 2000). According to Mayr and Kliegl (2000), task sets can be viewed as intricate retrieval structures, with multiple task sets interconnected through a shared "experimental context" node. The process of alternating between two or more tasks can be visualized as shifting the focus of working memory along these retrieval paths. The challenge of internal control lies in correctly positioning the focus of one's working memory within the pertinent retrieval structure. In mixed blocks, participants cannot focus on just one task; thus, they stay in the "experimental context" to reduce the average retrieval distance to all possible task sets. Our study involved a triple-task paradigm with three possible task sets, an increase from the typical dual-task studies. This increase in task sets and task-set combinations leads to greater uncertainty and coordinative complexity, resulting in longer response times. The probability of preparing correctly decreased significantly from 1:3 in dual-task studies to 1:7 task-set combinations in our triple-task study. In real-world scenarios, such as driving a car, the probabilities may be much lower, as dozens of potential tasks must be coordinated depending on the traffic situation, which requires managing and switching between multiple task sets.

In exploring how participants manage multiple tasks, we noted a pronounced preference for the visual-manual task. This aligns with findings from Schumacher et al. (2001), where similar tendencies were reported. Recognizing these task preferences is pivotal as it provides a lens through which we can interpret multi-tasking costs that arise with escalating task complexity. These costs were evident in the performance of both prepared and unprepared participants, underscoring the cognitive load it imposes.

Alternative Explanation for Different Inter-Response-Intervals

Hirsch et al. (2021) propose that during dual-task training, participants develop a hierarchical control system that stores the individual tasks and the entire task-pair set. This suggests that when faced with a dual task, participants retrieve the combination of the two tasks rather than the individual tasks themselves. Applying this concept to our study, it is plausible that the dual-task training in the preparation phase created a task-pair set that is now being retrieved, even with the addition of a third task in the assessment phase. Instead of creating an entirely new set for the triple task, the existing (learned) task-pair set from the dual-task training may be extended to incorporate the additional task. In the case of the unprepared participants, who are facing all tasks as new, a task-pair set is likely formed in a manner similar to what has been observed in dual-task research. Specifically, the auditory-vocal task tends to be processed last after completing the other tasks. These insights suggest that the formation and retrieval of task sets play a crucial role in how participants coordinate and execute multiple tasks, with prior training influencing the strategies employed when faced with novel task combinations.

Interpretation of Multi-Task Costs

Multi-task costs are a central aspect of our study as they provide a measure of the cognitive load and efficiency in task execution. Traditionally, these costs have been evaluated by comparing performance on dual tasks to single tasks, as detailed in seminal works by Schumacher et al. (2001) and Tombu and Jolicoeur (2004). The assumption is that with sufficient training, participants can improve their allocation of cognitive resources, leading to enhanced response selection and potential task automatization. Ideally, with extensive practice, multi-task response times could approach those of single tasks, potentially reducing multi-task costs to zero.

However, our study presents a more complex scenario. Despite the training, differences in response times and error rates persisted across all levels of task complexity throughout the training sessions, indicating enduring multi-task costs. This suggests that the number of tasks and the coordination required to manage them are substantial in these costs. While classic dual tasks increase coordination demands by the number of possible responses, our study introduces the additional complexity of multiple stimuli and their associated response combinations. It appears that this coordination could be so working memory demanding that either the duration of our training was insufficient, or it may be inherently challenging to eliminate multi-task costs entirely (see also, Schubert et al., 2024). Therefore, the effective coordination of multiple subtasks appears to be more critical when the task combinations and task sets expand and should be a focal point in cognitive modeling.

Triple Tasks in the Context of Multi-tasking Models

Our findings validate the impact of training on task performance, illustrating distinct improvements across various task conditions. It is theorized that such training develops specialized task sets, enhancing the efficiency of these tasks (Schubert & Strobach, 2018). This enhancement in executive functions, particularly regarding coordination and resource allocation (cf. Strobach et al., 2014), equips participants with skills that lead to a more effective activation of these task sets in working memory. We anticipated this would give prepared participants an edge in the triple tasks, an advantage evident in the earlier stages. Although prepared participants initially showed quicker response times across all task complexities despite introducing a new task, by the end of the assessment phase, the performance gap between the prepared and unprepared groups had almost closed (55 ms difference), yet significant multi-task costs persisted.

The frameworks for multi-tasking, such as EPIC (Meyer & Kieras, 1999) and Wickens' resource model (Wickens, 1981), seek to predict task-related processes and behaviors. These models have been instrumental in understanding single and dual tasks within laboratory settings but face challenges when applied to more complex, real-world multi-tasking scenarios. Klein et al. (2003) distinguish between the micro-cognitive analysis typical of lab studies and the macro-cognitive analysis necessary for real-world applications, noting the limited ecological validity of the former. Indeed, Hoffmann et al. (2019) have highlighted the inadequacies of these models in accounting for the strategies and task prioritizations that emerge from training, which are not adequately explained by the structural predictions of EPIC or the resource allocations proposed by Wickens.

In particular, structural models like EPIC assume that tasks can be processed with equal speed and efficiency, whether in isolation or combination. However, training studies reveal that this assumption holds for only a subset of tasks, often just one within a more complex array (Pashler, 1994). This suggests that the efficiency of task processing in dual-task situations can be influenced by various factors, including the nature of the tasks, the individual's experience with the tasks, and the specific demands of the tasks. As demanded by triple tasks, the physical coordination required for multiple simultaneous actions introduces a level of coordinative complexity that can exceed our capacity for synchronicity. This leads to a shift from coordinative to sequential complexity (Mayr & Kliegl, 2000), much like the linguistic requirement to articulate words in sequence to form coherent sentences. In such cases, the central bottleneck is not necessarily cognitive but rather stems from the biomechanical constraints of our effectors.

The EPIC model also does not account for individuals' varied prioritizations or strategies, demonstrated even in dual-task conditions (Hommel, 2020). Similarly, while insightful, Wickens' resource model does not fully encapsulate the dynamic prioritization that can result from the interplay between multiple tasks and the available cognitive resources. Given these considerations, our study suggests that existing multi-tasking models may require re-evaluation and expansion to incorporate the complexities observed in training effects, particularly in scenarios that involve more than two tasks. This highlights the necessity for further research to probe deeper into the nature of triple-task scenarios and refine the predictive power of multi-tasking frameworks for complex, real-life environments.

Limitations of the Study

Our investigation into multi-tasking has yielded insights that contribute to understanding this complex cognitive process. However, recognizing the limitations of our study is essential for accurately interpreting and applying our findings. Primarily, the task design aimed to emulate real-world multi-tasking complexity may not fully capture the unpredictable nature of such scenarios outside the laboratory. The controlled lab environment, while necessary for experimental rigor, might not reflect the influence of real-world variables on behavior, thus questioning the external validity of our results.

When interpreting the results, it is crucial to consider that although both groups were highly trained, the number of completed sessions varied, with the prepared group completing up to 17 sessions. Despite meeting the predetermined sample size requirements, the statistical power of the sample should be interpreted with caution. The replicability of the findings, particularly concerning the between-subject effects observed between the two groups, remains to be determined through further research.

Furthermore, while the study observed a high error rate with triple tasks, this does not necessarily undermine the results' legitimacy or the outcomes' quality. High error rates can indicate the complexity and challenge of triple tasks, which require participants to juggle multiple tasks simultaneously. Despite the high error rates, the study yielded significant findings and demonstrated the potential benefits of training on task performance. Therefore, while the high error rate is a limitation, it does not detract from the overall value and contributions of the study. In light of these considerations, our study should be seen as a stepping stone, offering preliminary insights while also highlighting the need for further, more extensive research to build upon and extend our understanding of multi-tasking across diverse and complex environments.

Conclusion

Our investigation highlights the need to consider task complexity for future explorations in multi-tasking research. An increase in the number of task sets significantly affects response times, particularly in participants who have not undergone task-specific training. Those with dual-task training initially exhibited superior performance, but this advantage diminished over time. Intriguingly, different strategies for managing the triple tasks emerged between the two groups, with more task-set combinations presenting a notable challenge to coordination efforts. The results suggest that individuals with skills such as task coordination acquired in specific subtasks can indeed benefit from scenarios with new tasks, given sufficient training. Moreover, the formation of task sets (or maybe task set pairs) seems to play a pivotal role in processing and coordinating tasks. Once established and expanded (with a new task), it influences the establishment of further task sets (pairs). This resilience poses a considerable challenge for current cognitive models to accurately predict the interaction between stimulus-response sets and their corresponding response times. Our research underscores the necessity for additional studies that delve into the dynamics of inter(sub)task coordination and the prioritization of multiple tasks. As multi-tasking remains an essential aspect of daily life, the continuous refinement of cognitive models is paramount to keep pace with discoveries and the ever-growing complexity of multi-tasking behaviors. Moving forward, the adaptability of these models will be critical in understanding and predicting human behavior in an increasingly multitasking-oriented world.

Declarations

Author contributions

M.S. = Maximilian Stefani, *M*.Sa. = Marian Sauter, W.*M*. = Wolfgang Mack.
Conceptualization: *M*.S.; Data curation: *M*.S.; Formal analysis: *M*.S.; Investigation: *M*.S. (lead) and *M*.Sa.; Methodology: *M*.S. (lead) and W.*M*. ; Project administration: *M*.S.; Resources: W.*M*.; Software: *M*.S.; Validation: *M*.S. (lead) and *M*.Sa.; Visualization: *M*.S.; Writing – original draft: *M*.S.; Writing - review & editing: *M*.S. (lead), *M*.Sa. and W.*M*.;

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Competing interests

The authors have no competing interests to declare relevant to this article's content.

Ethics approval

All procedures performed in this study were accepted by the ethical committee of the University of the Bundeswehr Munich and in accordance with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards.

Consent to participate

Written informed consent for participation and use of participants' data was obtained prior to the study. Participants were informed that participation was voluntary, that they could withdraw their consent at any time during the study, that their data were processed in anonymized form, and that they could ask to delete their data via their personalized code for at least three months after participation.

Consent for publication

The use of participants' data for publication was obtained prior to the study within the written informed consent for participation.

Data, Material, and Code availability

The datasets, material, and code generated as part of our study and/or analyzed during the current study are available at osf.io: https://osf.io/fr4wa/?view_only=f3110a5833a84f18b5486ec449dfde1c. This study was not pre-registered.

References

Barnett, S. *M*., & Ceci, S. J. (2002). When and where do we apply what we learn? A taxonomy for far transfer. *Psychological Bulletin*, *128*(4), 612–637. https://doi.org/10.1037/0033-2909.128.4.612

Bherer, L., Kramer, A. *F*., Peterson, *M*. S., Colcombe, S., Erickson, K., & Becic, E. (2008). Transfer effects in task-set cost and dual-task cost after dual-task training in older and younger adults: Further evidence for cognitive plasticity in attentional control in late adulthood. *Experimental Aging Research*, *34*(3), 188–219. https://doi.org/10.1080/03610730802070068

Brainard, D., Kleiner, *M*., & Diederick, C. (2016). *Psychtoolbox-3*. http://www.psychtoolbox.org

Faul, *F*., Erdfelder, E., Buchner, A., & Lang, A.-G. (2009). Statistical power analyses using G*Power 3.1: Tests for correlation and regression analyses. *Behavior Research Methods*, *41*(4), 1149–1160. https://doi.org/10.3758/BRM.41.4.1149

Garner, K. G., & Dux, P. E. (2023). Knowledge generalization and the costs of multi-tasking. *Nature Reviews Neuroscience*, *24*, 98–112. https://doi.org/10.1038/s41583-022-00653-x

Göthe, K., Oberauer, K., & Kliegl, R. (2016). Eliminating dual-task costs by minimizing crosstalk between tasks: The role of modality and feature pairings. *Cognition*, *150*, 92–108. https://doi.org/10.1016/j.cognition.2016.02.003

Greiner, B. (2015). Subject pool recruitment procedures: Organizing experiments with ORSEE. *Journal of the Economic Science Association*, *1*(1), 114–125. https://doi.org/10.1007/s40881-015-0004-4

Hazeltine, E., Ruthruff, E., & Remington, R. W. (2006). The role of input and output modality pairings in dual-task performance: Evidence for content-dependent central interference. *Cognitive Psychology*, *52*(4), 291–345. https://doi.org/10.1016/j.cogpsych.2005.11.001

Koch, I. (2009). The role of crosstalk in dual-task performance: Evidence from manipulating response-code overlap. *Psychological Research*, *73*(3), 417–424. https://doi.org/10.1007/s00426-008-0152-8

Kramer, A. *F*., Larish, J. *F*., & Strayer, D. L. (1995). Training for Attentional Control in Dual Task Settings: A Comparison of Young and Old Adults. *Journal of Experimental Psychology: Applied*, *1*(1), 50–76. https://doi.org/10.1037/1076-898X.1.1.50

Liepelt, R., Strobach, T., Frensch, P., & Schubert, T. (2011). Improved intertask coordination after extensive dual-task practice. *Quarterly Journal of Experimental Psychology (2006)*, *64*(7), 1251–1272. https://doi.org/10.1080/17470218.2010.543284

Lyphout-Spitz, *M*., Maquestiaux, *F*., Ruthruff, E., & Chaloyard, S. (2024). Uncorking the central bottleneck: Even novel tasks can be performed automatically. *Journal of Experimental Psychology: Human Perception and Performance*, *50*(1), 74–98. https://doi.org/10.1037/xhp0001169

Maquestiaux, *F*., Laguë-Beauvais, *M*., Ruthruff, E., & Bherer, L. (2008). Bypassing the central bottleneck after single-task practice in the psychological refractory period paradigm: Evidence for task automatization and greedy resource recruitment. *Memory & Cognition*, *36*(7), 1262–1282. https://doi.org/10.3758/MC.36.7.1262

Maquestiaux, *F*., Laguë-Beauvais, *M*., Ruthruff, E., Hartley, A., & Bherer, L. (2010). Learning to bypass the central bottleneck: Declining automaticity with advancing age. *Psychology and Aging*, *25*(1), 177–192. https://doi.org/10.1037/a0017122

Maquestiaux, *F*., Ruthruff, E., Defer, A., & Ibrahime, S. (2018). Dual-task automatization: The key role of sensory-motor modality compatibility. *Attention, Perception & Psychophysics*, *80*(3), 752–772. https://doi.org/10.3758/s13414-017-1469-4

Mayr, U., & Kliegl, R. (1993). Sequential and coordinative complexity: Age-based processing limitations in figural transformations. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *19*(6), 1297–1320. https://doi.org/10.1037/0278-7393.19.6.1297

Mayr, U., & Kliegl, R. (2000). Task-set switching and long-term memory retrieval. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *26*(5), 1124–1140. https://doi.org/10.1037/0278-7393.26.5.1124

Meyer, D. E., & Kieras, D. E. (1997a). A computational theory of executive cognitive processes and multiple-task performance: Part 2. Accounts of psychological refractory-period phenomena. *Psychological Review*, *104*(4), 749. https://doi.org/2F10.1037/2F/2F0033-295X.104.4.749

Meyer, D. E., & Kieras, D. E. (1997b). A computational theory of executive cognitive processes and multiple-task performance: Part I. Basic mechanisms. *Psychological Review*, *104*(1), 3. https://doi.org/10.1037/0033-295x.104.1.3

Nett, T. (2017). *VoiceExperiment: This package allows the analysis of vocal responses to psychological experiments. R package version 1.0.2*.

Oldfield, R. C. (1971). THE ASSESSMENT AND ANALYSIS OF HANDEDNESS: THE EDINBURGH INVENTORY. *Neuropsychologia*, *9*, 97–113.

Pashler, H. (1984). Processing stages in overlapping tasks: Evidence for a central bottleneck. *Journal of Experimental Psychology: Human Perception and Performance*, *10*(3), 358–377. https://doi.org/10.1037//0096-1523.10.3.358

RStudio Team. (2016). *RStudio: Integrated Development Environment for R*. RStudio, Inc. http://www.rstudio.com/

Ruthruff, E., Pashler, H., & Klaassen, A. (2001). Processing bottlenecks in dual-task performance: Structural limitation or strategic postponement? *Psychonomic Bulletin & Review*, *8*(1), 73–80. https://doi.org/10.3758/BF03196141

Ruthruff, E., van Selst, *M*., Johnston, J. C., & Remington, R. (2006). How does practice reduce dual-task interference: Integration, automatization, or just stage-shortening? *Psychological Research*, *70*(2), 125–142. https://doi.org/10.1007/s00426-004-0192-7

Schubert, T., Kübler, S., & Strobach, T. (2024). A mechanism underlying improved dual-task performance after practice: Reviewing evidence for the memory hypothesis. *Psychonomic Bulletin & Review*. https://doi.org/10.3758/s13423-024-02498-0

Schubert, T., Liepelt, R., Kübler, S., & Strobach, T. (2017). Transferability of Dual-Task Coordination Skills after Practice with Changing Component Tasks. *Frontiers in Psychology*, *8*, 956. https://doi.org/10.3389/fpsyg.2017.00956

Schubert, T., & Strobach, T. (2018). Practice-related optimization of dual-task performance: Efficient task instantiation during overlapping task processing. *Journal of Experimental Psychology: Human Perception and Performance*, *44*(12), 1884–1904. https://doi.org/10.1037/xhp0000576

Schumacher, E. H., Seymour, T. L., Glass, J. *M*., Fencsik, D. E., Lauber, E. J., Kieras, D. E., & Meyer, D. E. (2001). Virtually Perfect Time Sharing in Dual-Task Performance: Uncorking the Central Cognitive Bottleneck. *Psychological Science*, *12*(2), 101–108. https://doi.org/10.1111/1467-9280.00318

Sommer, W., Leuthold, H., & Schubert, T. (2001). Multiple bottlenecks in information processing? An electrophysiological examination. *Psychonomic Bulletin & Review*, *8*(1), 81–88. https://doi.org/10.3758/bf03196142

Stefani, *M*., Sauter, *M*., Eichert, *F*., & Mack, W. (2022). Expanding dual-task research by a triple-task. *Open Psychology*, *4*(1), 152–174. https://doi.org/10.1515/psych-2022-0008

Strobach, T., Frensch, P. A., Soutschek, A., & Schubert, T. (2012). Investigation on the improvement and transfer of dual-task coordination skills. *Psychological Research*, *76*(6), 794–811. https://doi.org/10.1007/s00426-011-0381-0

Strobach, T., Liepelt, R., Pashler, H., Frensch, P. A., & Schubert, T. (2013). Effects of extensive dual-task practice on processing stages in simultaneous choice tasks. *Attention, Perception & Psychophysics*, *75*(5), 900–920. https://doi.org/10.3758/s13414-013-0451-z

Strobach, T., Salminen, T., Karbach, J., & Schubert, T. (2014). Practice-related optimization and transfer of executive functions: A general review and a specific realization of their mechanisms in dual tasks. *Psychological Research*, *78*(6), 836–851. https://doi.org/10.1007/s00426-014-0563-7

Strobach, T., & Schubert, T. (2017). No evidence for task automatization after dual-task training in younger and older adults. *Psychology and Aging*, *32*(1), 28–41. https://doi.org/10.1037/pag0000144

Tombu, *M*., & Jolicoeur, P. (2004). Virtually no evidence for virtually perfect time-sharing. *Journal of Experimental Psychology. Human Perception and Performance*, *30*(5), 795–810. https://doi.org/10.1037/0096-1523.30.5.795

Wickham, H. (2017). *tidyverse: Easily Install and Load the "Tidyverse."* https://CRAN.R-project.org/package=tidyverse

Appendix

Table 2

Repeated measures ANOVA for response times of the visual-manual and auditory-vocal task in the preparation phase with Greenhouse-Geisser corrections for violations of sphericity with the within-subject factors complexity (simple and medium) and session (1 – 9)

	df	*F*	*p*	*η²p*
Visual-manual task				
Session	2.33, 28.00	6.52	.003	0.352
Complexity	1, 12	0.84	.378	0.065
Session ✻ complexity	1.95, 23.38	10.12	< .001	0.457
Auditory-vocal task				
Session	2.48, 29.81	4.92	.01	0.291
Complexity	1, 12	18.98	< .001	0.613
Session ✻ Complexity	2.89, 34.62	2.28	.098	0.16

Table 3

Repeated measures ANOVA for error rates of the visual-manual and auditory-vocal task in the preparation phase with Greenhouse-Geisser corrections for violations of sphericity with the within-subject factors complexity (simple and medium) and session (1 – 9)

	df	*F*	*p*	*η²p*
Visual-manual task				
Session	1.86, 22.28	5.64	0.012	0.32
Complexity	1, 12	0.31	0.589	0.025
Session ✻ complexity	3.13, 37.56	1.58	0.208	0.117
Auditory-vocal task				
Session	1.48, 17.78	0.47	0.578	0.037
Complexity	1, 12	1.38	0.262	0.103
Session ✻ complexity	3.05, 36.57	1.44	0.247	0.107

Table 4

Repeated measures ANOVA for response times of the visual-manual, visual-pedal, and auditory-vocal task in the assessment phase with Greenhouse-Geisser corrections for violations of sphericity with the within-subject factors complexity (simple and medium) and session (1 – 8) and the between-subject factor preparation status (unprepared and prepared)

	df	*F*	*p*	η^2p
Visual-manual task				
Session	2.96, 73.95	99.42	< .001	0.799
Session ✻ preparation status	2.96, 73.95	5.90	.001	0.191
Complexity	1.02, 25.48	36.31	< .001	0.592
Complexity ✻ preparation status	1.02, 25.48	0.62	.441	0.024
Session ✻ complexity	3.43, 85.76	32.56	< .001	0.566
Session ✻ complexity ✻ preparation status	3.43, 85.76	1.23	.306	0.047
Preparation status	1.00, 25	1.99	.171	0.074
Visual-pedal task				
Session	2.51, 62.75	55.17	< .001	0.688
Session ✻ preparation status	2.51, 62.75	5.39	.004	0.177
Complexity	1.14, 28.39	165.35	< .001	0.869
Complexity ✻ preparation status	1.14, 28.39	7.80	.007	0.238
Session ✻ complexity	5.28, 132.06	7.55	< .001	0.232
Session ✻ complexity ✻ preparation status	5.28, 132.06	2.51	.030	0.091
Preparation status	1.00, 25	2.14	.156	0.079
Auditory-vocal task				
Session	3.29, 82.15	37.88	< .001	0.602
Session ✻ preparation status	3.29, 82.15	2.70	.046	0.097
Complexity	1.12, 27.88	83.75	< .001	0.77
Complexity ✻ preparation status	1.12, 27.88	5.70	.021	0.186
Session ✻ complexity	5.04, 125.95	13.27	< .001	0.347
Session ✻ complexity ✻ preparation status	5.04, 125.95	1.28	.276	0.049
Preparation status	1.00, 25	11.76	.002	0.32

Table 5

Repeated measures ANOVA for error rates of the visual-manual, visual-pedal, and auditory-vocal task in the assessment phase with Greenhouse-Geisser corrections for violations of sphericity with the within-subject factors complexity (simple and medium) and session (1 – 8) and the between-subject factor preparation status (unprepared and prepared)

	df	*F*	*p*	$\eta^2 p$
Visual-manual task				
Session	3.40, 84.93	8.47	< .001	0.253
Session ✻ preparation status	3.40, 84.93	0.33	0.83	0.013
Complexity	1.29, 32.20	4.92	0.026	0.164
Complexity ✻ preparation status	1.29, 32.20	2.63	0.107	0.095
Session ✻ complexity	7.07, 176.70	0.46	0.865	0.018
Session ✻ complexity ✻ preparation status	7.07, 176.70	0.90	0.511	0.035
Preparation status	1.00, 25	0.00	0.971	0
Visual-pedal task				
Session	4.68, 117.10	2.54	0.035	0.092
Session ✻ preparation status	4.68, 117.10	1.97	0.093	0.073
Complexity	1.77, 44.12	33.74	< .001	0.574
Complexity ✻ preparation status	1.77, 44.12	4.19	0.026	0.143
Session ✻ complexity	7.96, 198.93	3.79	< .001	0.132
Session ✻ complexity ✻ preparation status	7.96, 198.93	0.93	0.494	0.036
Preparation status	1.00, 25	2.52	0.125	0.092
Auditory-vocal task				
Session	3.01, 75.26	1.60	0.196	0.06
Session ✻ preparation status	3.01, 75.26	0.49	0.693	0.019
Complexity	1.68, 41.92	9.42	< .001	0.274
Complexity ✻ preparation status	1.68, 41.92	1.01	0.362	0.039
Session ✻ complexity	6.58, 164.41	4.15	< .001	0.142
Session ✻ complexity ✻ preparation status	6.58, 164.41	0.92	0.489	0.035
Preparation status	1.00, 25	0.12	0.732	0.005

Discussion

Despite the extensive research into multitasking spanning several decades, the majority of studies have focused on tasks that involve managing two actions at once, commonly referred to as dual tasks (f.e., Kiesel et al., 2010; Pashler & Christian, 1994; Ruthruff et al., 2003; Strobach, 2023). Consequently, many consider a dual task to be synonymous with multitasking (see the handbook of multitasking, Kiesel et al., 2022). As a result, the existing body of knowledge, including multitasking models, is predominantly based on the dynamics of dual-task scenarios. This focus on dual tasks is not without merit; it has consistently yielded valuable insights. However, it raises a critical question: Are we genuinely exploring the full spectrum of multitasking, or are we merely examining a subset of it, which might be more aptly described as task competition rather than multitasking? This dissertation aims to build upon the existing foundation of multitasking research by introducing a third concurrent task. This addition aims to create a more complex multitasking environment, thereby providing a deeper understanding of how individuals manage multiple tasks simultaneously.

Summary of contribution 1

Laboratory-based multitasking research predominantly utilizes overly simplistic dual-task paradigms that do not adequately reflect the complexities encountered in everyday multitasking environments. The study of Contribution 1 enhances the traditional dual-task paradigm by incorporating an additional third task. Participants had to perform visual-manual, visual-pedal, and auditory-vocal tasks over three sessions. The objective was to explore how combining these three tasks affects response times and associated costs. In Experiment 1 ($N = 19$), the stimulus-response pairings (location-hand, color-feet, and pitch-voice vs. color-hand, location-feet, and pitch-voice) were tested within participants, and in Experiment 2 ($N = 44$) between participants. The findings revealed that the escalation in response time when transitioning from dual to triple tasks represented only 43% of the increase observed when moving from single to dual tasks, indicating a non-linear cost associated with adding more tasks. Additionally, response times for each subtask were consistently higher in the triple-task condition compared to both single and dual tasks. This deviates from typical dual-task scenarios where usually only one response is delayed. Furthermore, in triple tasks, unlike dual tasks, the coordination of tasks appears to play a more significant role than the traditionally emphasized relationships between stimulus and response based on their modality and ideomotor compatibility. Remarkably, the two visual tasks (visual-manual and visual-pedal) within the triple-task scenario elicited similar response times, a finding that deviates from previous assumptions predicting a distinct sequence of responses. We posit that the observed phenomena can be attributed to variations in how tasks are coordinated. The study underscores the limitations of current multitasking research, which focuses narrowly on dual tasks, and suggests that incorporating more complex task configurations could enhance the applicability and relevance of research findings.

Summary of contribution 2

In the second contribution, we investigated the complexities of transitioning from dual-task to triple-task scenarios after training, extending the scope beyond the primarily studied dual-task training studies. The research compared the impact of triple-task performance on two distinct participant groups: those unprepared for single, dual, or triple tasks (N = 14) and those previously prepared through training in single and dual tasks (N = 13). During the preparation phase, the prepared group underwent nine sessions involving a visual-manual and an auditory-vocal task as single and dual tasks. By the end of this training, dual-task costs (dual-task vs. single-task performance) were observed only in the auditory-vocal task, aligning with findings from other dual-task training studies. In the subsequent assessment phase, both the prepared and unprepared groups performed eight sessions that included single, dual, and triple tasks of varying complexity, reflecting simple (single tasks), medium (dual tasks), and complex (triple tasks) conditions. A visual-pedal task was introduced, extending the existing dual-task paradigm to a triple-task scenario. Despite the initial advantage observed in the prepared group, this advantage diminished throughout the sessions. Interestingly, the two groups employed distinct strategies for processing within the triple task. Descriptively, the prepared group responded first with the previously learned visual-manual and auditory-vocal dual task, followed by the visual-pedal task. In contrast, the unprepared group responded in the order visual-manual, visual-pedal, and auditory-vocal. The findings underscore the significance of task coordination strategies in multitasking scenarios and shed light on the intricacies of managing the transition from dual to triple tasks. The study demonstrates that training can facilitate applying skills acquired from specific tasks to novel task combinations, with the formation of specific task sets playing a pivotal role in processing and coordination. However, the persistence of multitasking costs, even after extensive training, challenges traditional assumptions about eliminating such costs through practice alone.

Central findings

Triple tasks a simple extension of dual tasks?

Research on dual tasks has shown that combining two single tasks into one dual task typically results in diminished performance (Welford, 1952). Specifically, it takes more time and leads to more errors when managing a dual task than handling each separately. Given these findings, our initial hypothesis posited that performance would degrade further by introducing a triple task. We anticipated that participants would perform best on the single task, followed by the dual tasks, and worst on the triple task. This pattern was indeed observed, although the performance varied significantly among the three possible dual tasks, which I will discuss in the following section.

We theorized that the degree of compatibility between tasks might result in either lower or higher interference (Göthe et al., 2016), but the response times showed even greater variability. However, before delving deeper into these results, it is essential to recall that when both single tasks and their combined dual task are executed in experimental blocks, the performance of the single task remains largely unaffected in mixed (heterogeneous) blocks, as opposed to homogeneous blocks where only a single task is performed (Schumacher et al., 2001, see especially Experiment 3). Extending these findings to triple tasks, one might expect that adding a third task would not significantly impact the performance of dual and single tasks. In theory, each task should be processed optimally. Contrary to this assumption, our findings indicate that introducing a third task can significantly affect the performance of both dual and single tasks. Participants often coordinated the manual and pedal tasks, responding simultaneously in almost all cases, with a response time difference of less than 100 milliseconds. For instance, the study by (Liepelt, Fischer, et al., 2011) demonstrates that the combination of manual and pedal dual tasks does not lead to an automatic coupling of the two tasks. Nonetheless, research into bimanual coordination, such as studies involving piano players, has demonstrated improved performance (fewer errors) when both hands are synchronized in their actions (e.g., when the hands play a shared rhythm as opposed to two distinct rhythms) (Miller & Ulrich, 2008; Ruthruff et al., 2001). Notably, the coordination effect observed in our first contribution was relatively stable across three sessions, suggesting a consistent pattern. Although alternating stimulus-response pairings might contribute to this phenomenon, they do not fully explain the observed effects. Instead, strategic components appear to play a more significant role in managing multiple tasks, such as in a triple-task scenario, compared to a dual-task scenario. Furthermore, it seemed that the tasks in our triple-task studies were structured in a hierarchical manner (Hirsch et al., 2018, 2021), which may also influence how tasks are processed and coordinated. The concept of a hierarchical task structure could be pivotal in understanding how individuals manage multiple tasks simultaneously, particularly in complex multitasking environments like those involving triple tasks. Hierarchical task structuring refers to the organization of tasks in a manner where some tasks are prioritized or processed sequentially based on their cognitive demands or the individual's goals. The hierarchical model of task processing suggests that tasks are not processed in isolation but are organized according to a hierarchy of goals and subgoals (Hirsch et al., 2018). This model is supported by cognitive control theories, which propose that higher-level cognitive processes govern the allocation of attention and resources to lower-level tasks based on their relevance to the overarching goal (Botvinick et al., 2009; Strobach, 2023). Empirical studies, such as those by Hirsch and colleagues 2018, 2021, provide evidence for the existence of a multi-component hierarchical control system in cognitive tasks. These studies demonstrate that when individuals are faced with multiple tasks, they often employ a strategy that involves prioritizing tasks that are more critical or demanding, thereby forming a cognitive hierarchy.

Furthermore, the concept of hierarchical organization is not limited to cognitive tasks in dual-task research but extends to broader behavioral and organizational studies from the macro level. In complex work environments, e.g., the Action Regulation Theory (Zacher & Frese, 2018) provides a comprehensive framework for understanding how actions are regulated. This framework underscores the importance of hierarchical structuring in regulating actions, suggesting that individuals and organizations systematically prioritize and sequence activities to achieve their goals efficiently. Similar to the hierarchical model of task processing in cognitive studies, Action Regulation Theory posits that actions are organized in a hierarchy of goals, where higher-level objectives influence the selection and execution of lower-level actions. This correspondence between cognitive (micro level) and organizational theories (macro level) demonstrates the universal applicability of hierarchical organizational principles, whether in processing multiple cognitive tasks or regulating actions in complex organizational environments when more cognitive control is needed.

In my opinion, in the context of multitasking, particularly when extending from dual to triple tasks, the hierarchical task structure becomes increasingly relevant. As observed in our first contribution, participants displayed a tendency to synchronize specific tasks (manual and pedal tasks), which suggests a strategic alignment or prioritization according to a hierarchy of task demands. More precisely, the participant forms a distinct pattern of response behavior, which appears to be independent of cognitive resources. This pattern likely represents an adaptive strategy to manage the increased complexity and cognitive load presented by adding a third task. While the first contribution involved completing several sessions, it raises the question of how specific training could impact task performance. This issue was investigated in greater depth in the second contribution.

Impact of training

Interestingly, in the training study (contribution 2), we could no longer observe that manual and pedal tasks were coupled. Instead, whether participants had previously undergone dual-task training was much more important. All those who had undergone dual-task training showed descriptively that the stimulus-response mapping learned previously (visual-manual and auditory-vocal) was preferred and responded to first. In contrast, participants who had not completed any training preferred the manual and pedal tasks before the auditory task, thus showing similar behavior to dual tasks, where the auditory task is apparently always responded to secondarily and where the greatest improvements can also be seen (Tombu & Jolicoeur, 2004).

The observation that participants who had previously practiced a dual task also had advantages in the triple task raises questions about how information is memorized and how tasks are learned. Hazeltine and Schumacher (2016) and Schumacher and Hazeltine (2016) proposed that task files are formed and retrieved accordingly, but these files only contain one of the three tasks. In contrast, Hirsch et al. (2021) suggests that not only the individual task but also the entire task-pair set is "saved", meaning that the combination of task 1 and task 2 is retrieved rather than the individual tasks, which in turn points to a hierarchical control system and thus confirms the conclusions from contribution 1. Our observations suggest that the dual-task training in our study may have created a mental set, or task-binding, that is now retrieved even with the addition of further tasks. Task-binding refers to the strong association formed between two tasks during training, which can persist even when a third task is introduced. Rather than creating an entirely new set for the triple task, a third task might extend the existing (learned) task-pair set. In the case where all tasks are new (untrained participants), a task-pair set is formed that is similar to the one observed in dual-task research, with the auditory-vocal task being processed last.

Analyzing the response times at the end of the triple-task training, we could not observe any significant differences between the group with prior dual-task training and those without training. All participants were able to improve significantly, even though the response times in all tasks were higher than in previous dual-task studies. This observation was consistent with the findings from the first contribution. Holding a large amount of information in working memory can be problematic (Schubert & Strobach, 2018). Dual-task studies have shown that the working memory system is necessary to maintain component task representations and coordinate these tasks during dual-task performance (Schubert et al., 2024). In the case of triple tasks, the increased amount of information appears to lead to an overall slowdown in response times. However, previous research on capacity constraints has primarily focused on dual tasks. As Schubert et al. (2024) points out, more complex tasks, such as triple tasks, require further investigation better to understand their effects on working memory and performance.

Summarizing the discussion in the training study, combining three possible tasks means that many stimulus-response mappings and their rules must be retained in working memory. Consequently, triple tasks cannot be considered simple stimulus-response time tasks that are processed without the influence of higher-order cognitive functions. Instead, top-down processes and cognitive control seem to play a much greater role (Schubert & Strobach, 2018; Schubert et al., 2024). However, with the current results, it is difficult to provide more precise information about the extent of cognitive control; further studies will need to be carried out in the future to address this issue.

Advantages and challenges of using triple tasks

Task selection

The triple-task training did not reveal any significant differences between the groups with and without prior dual-task training. All participants significantly improved their response times by the last session despite the response times across all tasks being higher than those observed in previous dual-task studies. This observation aligns with the findings from contribution 1, raising the question: Were the tasks selected for the triple task inappropriate?

One could argue that choosing two visual tasks from the outset leads to strong interference, as all models suggest that using the same resource (viewed from both capacity and structural perspectives) creates a bottleneck. However, when considering alternatives for a third task, options are limited. In terms of input modalities, visual and auditory stimuli have already been utilized, leaving only olfactory and tactile stimuli. However, these are challenging to implement due to the increased effort required, the habituation effect that sets in after a certain period, and the slow induction of olfactory stimuli, which complicates the study of cognitive functions. Moreover, the perception of these stimuli varies greatly from person to person, making it economically unfeasible to accommodate them. Regarding output modalities, oculomotor could have been utilized in addition to manual, vocal, and pedal responses (Hoffmann et al., 2019). However, this would place an even greater strain on the visual system. Using both hands might also have been possible, but this would likely cause greater interference than manual and pedal responses alone. Consequently, the combination of visual-manual, visual-pedal, and auditory-vocal tasks ensures relatively low interference and maintains a considerable degree of independence among the output modalities, making it the most suitable choice for the triple-task paradigm.

Despite the limitations in task selection, this dissertation demonstrates that a triple-task paradigm appears to utilize cognitive resources in a significantly different manner compared to traditional dual-task research. This finding highlights the importance of advancing dual-task research by testing new and extended paradigms. Although studies occasionally demonstrate the potential for predictions from laboratory settings to real-world applications, the assumptions derived from dual-task research remain limited to highly specialized areas. By exploring more complex paradigms, such as the triple task, we can expand our understanding of cognitive resource allocation and the limitations of human multitasking abilities. Investigating these extended paradigms will provide insights into the underlying mechanisms of cognitive processing and help bridge the gap between laboratory findings and real-world applications. As we continue pushing the boundaries of dual-task research, we can develop more comprehensive models that account for human cognition and behavior complexities in multitasking scenarios.

Multitasking costs calculation

Multitasking costs in dual-task research, where tasks are presented simultaneously (stimulus onset asynchrony (SOA) = 0 ms), are typically calculated by subtracting the performance in the single task from that in the dual task (Schumacher et al., 2001). For tasks with different stimulus onset asynchronies (SOAs) greater than zero (e.g., the "psychological refractory period effect" (Fischer & Janczyk, 2022; Telford, 1931)), the costs are demonstrated by the variation in the speed of processing the second task, which depends on the SOA. This occurs because the processing of the first task "hinders" the performance of the second task by blocking resources. In dual tasks, these calculations are relatively straightforward, as there can only be one comparison between the two tasks. However, triple tasks present several possible combinations for cost calculation. The triple task can be compared with the single task (similar to dual tasks), but also with the dual task, and the dual tasks themselves can be compared with the single tasks. In the presented studies, I have kept the calculations as simple as possible and attempted to make only straightforward comparisons between the tasks. However, future research could consider factors beyond task discrepancy, such as the number of stimulus-response mappings, possible combinations, and the occurrence of different tasks within an experimental task block. As previously discussed, a simple discrepancy calculation may not be sufficient to satisfactorily represent multitasking costs because all response times in the presented studies differ highly from dual-task studies. At this point, this consideration serves as a thought-provoking impulse to explore alternative calculation bases and expand our understanding of the factors contributing to multitasking costs in complex paradigms like the triple task.

Impact for current multitasking models

As described in the introduction, various models from dual-tasking research are based on different assumptions. Among the oldest are the structural models, such as the response selection bottleneck (Pashler, 1994) and their extensions, like the EPIC model (Meyer & Kieras, 1997a, 1997b). The response selection bottleneck model struggles to predict the results of the triple-task studies because it does not consider strategic or other cognitive components, such as task-pairing. These components are crucial for understanding how participants manage and prioritize multiple tasks. Without accounting for these factors, the model's predictive power is limited, as it cannot capture the complex interactions and adaptations that occur when individuals perform three simultaneous tasks. In contrast, the EPIC model can consider strategic aspects and include workload. However, the variables that need to be adjusted in the model must be scrutinized more closely. For example, the model may need to account for the increased cognitive load associated with managing three tasks and the potential for task-specific strategies and prioritization. Additionally, the model should consider how the effects of practice and learning might influence performance over time. Without a more detailed understanding of these variables and their impact on triple-task performance, making precise predictions using the EPIC model remains challenging. Resource models (Tombu & Jolicøeur, 2003), on the other hand, can provide better predictions, even if their definitions are unspecific. These models account for the number of tasks and their combination, recognizing that the more tasks, rules, and strategies pursued, the greater the load on working memory and the more resources required (Norman & Bobrow, 1975). In triple-task scenarios, the multitasking costs are likely higher than in dual-task situations, as the increased number of tasks and their combinations place a greater demand on cognitive resources. However, a simple comparison between single-task, dual-task, and triple-task performance may not suffice to capture the complexity of these interactions. Resource models, whether with single or multiple resources, cannot fully explain why an overload occurs despite their ability to consider various aspects of cognitive processing. This limitation stems from the lack of clarity regarding the nature of the resources themselves, their capacities, and how tasks are divided among them. Learning the tasks should save resources (e.g., by chunking), but the response times from dual-task studies could not be achieved until the last session. This discrepancy suggests that the increased complexity of the triple-task paradigm may have prevented participants from fully optimizing their performance, even with practice. Further research is needed to understand the factors contributing to this persistent overload and to develop models that can better account for the unique challenges posed by triple-task scenarios.

Limitations and future research

My concept of triple tasks was, and remains, an attempt to bridge the gap between micro-level and macro-level approaches. However, this gap is so substantial that the research presented here should be viewed merely as an initial step toward more comprehensive investigations. Moreover, while the triple task aligns closely with the micro-level — a deliberate focus — it remains somewhat distant from the macro-level, particularly due to the occasionally unexpected results observed in the studies (i.e., response grouping, long response times).

For example, the daily commute to work, as discussed in the chapter on "What is a task?". In addition to personal goals and motivations, the objectives of others also play a role. For instance, if you are in a partnership, your partner's specific goals might also influence your actions, such as purchasing a particular item. This scenario not only expands our personal tasks but also affects our behavior. While this example is quite specific, it illustrates the myriad of factors at the macro level that can impact the model for task accomplishment. It is crucial to recognize that micro-level models primarily consider intrinsic components. Although this exploration goes beyond basic research, when addressing multitasking, one should not ignore the goal of understanding our brain and, consequently, human behavior.

Turning back to the triple task itself, the extension of the dual task is not as straightforward as it might initially appear. Future research should explore how strategies, tasks, or the paradigm with an SOA of 0 ms affect performance.

For instance, rather than treating all tasks equally, it would be prudent to provide specific instructions that compel participants to deviate from their seemingly optimal task solutions. (Kübler et al., 2018) showed that control over task order significantly affects the processing of dual tasks, and the sequence in which tasks are processed can profoundly influence subsequent tasks (see, Bratzke et al., 2009; Ulrich et al., 2006). Modifying the processing order could lead to clearer insights into these dynamics.

One could also change the task combinations similar to the dual-task research of Hoffmann et al. (2019) and combine different response modalities or even further different stimulus-response mappings (Göthe et al., 2016).

Additionally, examining the impact of different SOAs on the triple task could be enlightening. Is it possible to observe the same PRP effect, where the processing time for tasks 2 and 3 increases with a shorter SOA, as seen in dual tasks (Pashler, 1984)? Investigating these questions could yield valuable insights into the underlying multitasking mechanisms and further bridge the divide between micro-level and macro-level approaches.

Conclusion

Continued research into dual-task scenarios is undoubtedly valuable; however, exploring triple-task situations represents a natural progression in the study of multitasking. In real-world settings, our brains rarely focus on a single stimulus; instead, we constantly switch and filter between different stimuli, deciding whether to respond or inhibit our responses. Furthermore, our goal-oriented behavior in these settings influences our actions and, thus, changes the observed behavior. Even in controlled laboratory environments, the cognitive processes under investigation are influenced by multiple factors simultaneously.

By extending our research to include triple tasks, we can gain deeper insights into the intricate workings of the human brain. This approach will enhance our understanding of how individuals manage and prioritize multiple tasks, especially when faced with increased cognitive demands. Investigating triple-task scenarios will shed light on the strategies employed by the brain to allocate attentional resources, process information, and coordinate responses effectively.

Moreover, studying triple tasks will contribute to the development of more accurate predictive models related to cognitive load and multitasking performance. These models will take into account the complex interactions between tasks and the hierarchical organization of cognitive processes, providing a more comprehensive representation of real-world multitasking situations.

This progression in research is essential for developing more realistic and applicable cognitive theories. By bridging the gap between micro level (laboratory findings) and macro level (real-world experiences), we can better understand how individuals navigate complex environments and adapt to the ever-increasing demands of modern life. Ultimately, this knowledge will inform the design of user interfaces, training programs, and work environments that optimize human performance and well-being in multitasking contexts.

References

Aksentijevic, A., & Gibson, K. (2012). Psychological Complexity and the Cost of Information Processing. *Theory & Psychology*, *22*(5), 572–590. https://doi.org/10.1177/0959354311423435

Anderson, J. R., Bothell, D., Byrne, M. D., Douglass, S., Lebiere, C., & Qin, Y. (2004). An Integrated Theory of the Mind. *Psychological Review*, *111*(4), 1036–1060. https://doi.org/10.1037/0033-295X.111.4.1036

Anderson, J. R., Taatgen, N. A., & Byrne, M. D. (2005). Learning to Achieve Perfect Timesharing: Architectural Implications of Hazeltine, Teague, and Ivry (2002). *Journal of Experimental Psychology. Human Perception and Performance*, *31*(4), 749–761. https://doi.org/10.1037/0096-1523.31.4.749

Band, G. P. H., & van Nes, F. T. (2006). Reconfiguration and the Bottleneck: Does Task Switching Affect the Refractory Period Effect? *European Journal of Cognitive Psychology*, *18*(4), 593–623. https://doi.org/10.1080/09541440500423244

Bherer, L., Kramer, A. F., Peterson, M. S., Colcombe, S., Erickson, K., & Becic, E. (2008). Transfer Effects in Task-Set Cost and Dual-Task Cost After Dual-Task Training in Older and Younger Adults: Further Evidence for Cognitive Plasticity in Attentional Control in Late Adulthood. *Experimental Aging Research*, *34*(3), 188–219. https://doi.org/10.1080/03610730802070068

Bornemann, E. (1942a). Untersuchungen Über Den Grad Der Geistigen Beanspruchung. *Arbeitsphysiologie*, *12*(2), 142–172. https://doi.org/10.1007/BF02605155

Bornemann, E. (1942b). Untersuchungen Über Den Grad Der Geistigen Beanspruchung. *Arbeitsphysiologie*, *12*(2), 173–191. https://doi.org/10.1007/BF02605156

Botvinick, M. M., Niv, Y., & Barto, A. G. (2009). Hierarchically Organized Behavior and Its Neural Foundations: A Reinforcement Learning Perspective. *Cognition*, *113*(3), 262–280. https://doi.org/10.1016/j.cognition.2008.08.011

Bratzke, D., Rolke, B., & Ulrich, R. (2009). The Source of Execution-Related Dual-Task Interference: Motor Bottleneck or Response Monitoring? *Journal of Experimental Psychology: Human Perception and Performance*, *35*(5), 1413–1426. https://doi.org/10.1037/a0015874

Cowan, N. (2001). The Magical Number 4 in Short-Term Memory: A Reconsideration of Mental Storage Capacity. *Behavioral and Brain Sciences*, *24*(1), 87–114. https://doi.org/10.1017/S0140525X01003922

Craik, F. I. M., & Bialystok, E. (2006). Planning and Task Management in Older Adults: Cooking Breakfast. *Memory & Cognition*, *34*(6), 1236–1249. https://doi.org/10.3758/BF03193268

de Jong, R. (1995). The Role of Preparation in Overlapping-Task Performance. *The Quarterly Journal of Experimental Psychology Section A*, *48*(1), 2–25. https://doi.org/10.1080/14640749508401372

Dixon, S. R., Wickens, C. D., & Chang, D. (2003). Comparing Quantitative Model Predictions to Experimental Data in Multiple-Uav Flight Control. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, *47*, 104–108. https://doi.org/10.1177/154193120304700122

Dreisbach, G., & Wenke, D. (2011). The Shielding Function of Task Sets and Its Relaxation During Task Switching: Journal of Experimental Psychology: Learning, Memory, and Cognition. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *37*(6), 1540–1546. https://doi.org/10.1037/a0024077

Duncan, J. (1979). Divided Attention: The Whole Is More Than the Sum of Its Parts: Journal of Experimental Psychology: Human Perception and Performance. *Journal of Experimental Psychology: Human Perception and Performance*, *5*(2), 216–228. https://doi.org/10.1037/0096-1523.5.2.216

Dux, P. E., Tombu, M. N., Harrison, S., Rogers, B. P., Tong, F., & Marois, R. (2009). Training Improves Multitasking Performance by Increasing the Speed of Information Processing in Human Prefrontal Cortex. *Neuron*, *63*(1), 127–138. https://doi.org/10.1016/j.neuron.2009.06.005

Elsmore, T. F. (1994). SYNWORK1: A PC-based Tool for Assessment of Performance in a Simulated Work Environment. *Behavior Research Methods, Instruments, & Computers*, *26*(4), 421–426. https://doi.org/10.3758/BF03204659

Fischer, R., & Janczyk, M. (2022). Dual-Task Performance With Simple Tasks. In A. Kiesel, L. Johannsen, I. Koch, & H. Müller (Eds.), *Handbook of Human Multitasking* (pp. 3–36). Springer International Publishing. https://doi.org/10.1007/978-3-031-04760-2_1

Fothergill, S., Loft, S., & Neal, A. (2009). ATC-labAdvanced: An Air Traffic Control Simulator With Realism and Control. *Behavior Research Methods*, *41*(1), 118–127. https://doi.org/10.3758/BRM.41.1.118

Garner, K. G., & Dux, P. E. (2023). Knowledge Generalization and the Costs of Multitasking. *Nature Reviews Neuroscience*, *24*(2), 98–112. https://doi.org/10.1038/s41583-022-00653-x

Gobet, F., Lane, P. C. R., Croker, S., Cheng, P. C.-H., Jones, G., Oliver, I., & Pine, J. M. (2001). Chunking Mechanisms in Human Learning. *Trends in Cognitive Sciences*, *5*(6), 236–243. https://doi.org/10.1016/S1364-6613(00)01662-4

Göthe, K., Oberauer, K., & Kliegl, R. (2016). Eliminating Dual-Task Costs by Minimizing Crosstalk Between Tasks: The Role of Modality and Feature Pairings. *Cognition*, *150*, 92–108. https://doi.org/10.1016/j.cognition.2016.02.003

Greenwald, A. G., & Shulman, H. G. (1973). On Doing Two Things at Once: II. Elimination of the Psychological Refractory Period Effect. *Journal of Experimental Psychology*, *101*(1), 70–76. https://doi.org/10.1037/h0035451

Hackman, J. R. (1969). Toward Understanding the Role of Tasks in Behavioral Research. *Acta Psychologica*, *31*, 97–128. https://doi.org/10.1016/0001-6918(69)90073-0

Hambrick, D. Z., Oswald, F. L., Darowski, E. S., Rench, T. A., & Brou, R. (2010). Predictors of Multitasking Performance in a Synthetic Work Paradigm. *Applied Cognitive Psychology*, *24*(8), 1149–1167. https://doi.org/10.1002/acp.1624

Hazeltine, E., Aparicio, P., Weinstein, A., & Ivry, R. B. (2007). Configural Response Learning: The Acquisition of a Nonpredictive Motor Skill. *Journal of Experimental Psychology. Human Perception and Performance*, *33*(6), 1451–1467. https://doi.org/10.1037/0096-1523.33.6.1451

Hazeltine, E., Ruthruff, E., & Remington, R. W. (2006). The Role of Input and Output Modality Pairings in Dual-Task Performance: Evidence for Content-Dependent Central Interference. *Cognitive Psychology*, *52*(4), 291–345. https://doi.org/10.1016/j.cogpsych.2005.11.001

Hazeltine, E., & Schumacher, E. H. (2016). Understanding Central Processes. In *Psychology of Learning and Motivation* (pp. 195–245, Vol. 64). Elsevier. https://doi.org/10.1016/bs.plm.2015.09.006

Hazeltine, E., Teague, D., & Ivry, R. B. (2002). Simultaneous Dual-Task Performance Reveals Parallel Response Selection After Practice. *Journal of Experimental Psychology: Human Perception and Performance*, *28*(3), 527–545. https://doi.org/10.1037//0096-1523.28.3.527

Heuer, H. (1996). Dual-Task Performance. In *Handbook of perception and action. 3: Attention / ed. by O. Neumann*. Academic Press.

Hirsch, P., Koch, I., & Grundgeiger, T. (2022). Task Interruptions. In A. Kiesel, L. Johannsen, I. Koch, & H. Müller (Eds.), *Handbook of Human Multitasking* (pp. 145–188). Springer International Publishing. https://doi.org/10.1007/978-3-031-04760-2_4

Hirsch, P., Nolden, S., Declerck, M., & Koch, I. (2018). Common Cognitive Control Processes Underlying Performance in Task-Switching and Dual-Task Contexts. *Advances in Cognitive Psychology*, *14*(3), 62–74. https://doi.org/10.5709/acp-0239-y

Hirsch, P., Nolden, S., Philipp, A. M., & Koch, I. (2017). Hierarchical Task Organization in Dual Tasks: Evidence for Higher Level Task Representations. *Psychological Research*, *82*(4), 759–770. https://doi.org/10.1007/s00426-017-0851-0

Hirsch, P., Roesch, C., & Koch, I. (2021). Evidence for a Multicomponent Hierarchical Representation of Dual Tasks. *Memory & Cognition*, *49*(2), 350–363. https://doi.org/10.3758/s13421-020-01097-3

Hoffmann, M. A., Pieczykolan, A., Koch, I., & Huestegge, L. (2019). Motor Sources of Dual-Task Interference: Evidence for Effector-Based Prioritization in Dual-Task Control. *Journal of Experimental Psychology. Human Perception and Performance*, *45*(10), 1355–1374. https://doi.org/10.1037/xhp0000677

Hommel, B. (1998). Automatic Stimulus-Response Translation in Dual-Task Performance. *Journal of Experimental Psychology: Human Perception and Performance*, *24*(5), 1368–1384. https://doi.org/10.1037/0096-1523.24.5.1368

Johannsen, L., Van Humbeeck, N., & Krampe, R. (2022). Multitasking During Continuous Task Demands: The Cognitive Costs of Concurrent Sensorimotor Activities. In A. Kiesel, L. Johannsen, I. Koch, & H. Müller (Eds.), *Handbook of Human Multitasking* (pp. 37–81). Springer International Publishing. https://doi.org/10.1007/978-3-031-04760-2_2

Kahneman, D. (1973). *Attention and Effort*. Prentice Hall.

Kahneman, D., Treisman, A., & Gibbs, B. J. (1992). The Reviewing of Object Files: Object-Specific Integration of Information. *Cognitive Psychology*, *24*(2), 175–219. https://doi.org/10.1016/0010-0285(92)90007-O

Karbach, J., & Strobach, T. (2022). Multitasking Training. In A. Kiesel, L. Johannsen, I. Koch, & H. Müller (Eds.), *Handbook of Human Multitasking* (pp. 305–345). Springer International Publishing. https://doi.org/10.1007/978-3-031-04760-2_8

Kiesel, A., Johannsen, L., Koch, I., & Müller, H. (Eds.). (2022). *Handbook of Human Multitasking*. Springer International Publishing. https://doi.org/10.1007/978-3-031-04760-2

Kiesel, A., Steinhauser, M., Wendt, M., Falkenstein, M., Jost, K., Philipp, A. M., & Koch, I. (2010). Control and Interference in Task Switching–a Review. *Psychological Bulletin*, *136*(5), 849–874. https://doi.org/10.1037/a0019842

Koch, I., & Kiesel, A. (2022). Task Switching: Cognitive Control in Sequential Multitasking. In A. Kiesel, L. Johannsen, I. Koch, & H. Müller (Eds.), *Handbook of Human Multitasking* (pp. 85–143). Springer International Publishing. https://doi.org/10.1007/978-3-031-04760-2_3

Koch, I., Poljac, E., Müller, H., & Kiesel, A. (2018). Cognitive Structure, Flexibility, and Plasticity in Human Multitasking-An Integrative Review of Dual-Task and Task-Switching Research. *Psychological Bulletin*, *144*(6), 557–583. https://doi.org/10.1037/bul0000144

Kornblum, S., & Hasbroucq, T. (1990). Dimensional Overlap: Cognitive Basis for Stimulus-Response Compatibility— A Model and Taxonomy. *Psychological Review*, *97*(2), 18. https://doi.org/10.1037/0033-295X.97.2.253

Kübler, S., Reimer, C. B., Strobach, T., & Schubert, T. (2018). The Impact of Free-Order and Sequential-Order Instructions on Task-Order Regulation in Dual Tasks. *Psychological Research*, *82*(1), 40–53. https://doi.org/10.1007/s00426-017-0910-6

Kübler, S., Strobach, T., & Schubert, T. (2022). On the Organization of Task-Order and Task-Specific Information in Dual-Task Situations. *Journal of Experimental Psychology: Human Perception and Performance*, *48*(1), 94–113. https://doi.org/10.1037/xhp0000969

Künzell, S., Broeker, L., Dignath, D., Ewolds, H., Raab, M., & Thomaschke, R. (2018). What Is a Task? An Ideomotor Perspective. *Psychological Research*, *82*(1), 4–11. https://doi.org/10.1007/s00426-017-0942-y

Lebiere, C., R. Anderson, J., & Bothell, D. (2001). Multi-Tasking and Cognitive Workload in an ACT-R Model of a Simplified Air Traffic Control Task. https://doi.org/10.1184/R1/6617216.v1

Lien, M.-C., Schweickert, R., & Proctor, R. W. (2003). Task Switching and Response Correspondence in the Psychological Refractory Period Paradigm. *Journal of Experimental Psychology: Human Perception and Performance*, *29*(3), 692–712. https://doi.org/10.1037/0096-1523.29.3.692

Liepelt, R., Fischer, R., Frensch, P. A., & Schubert, T. (2011). Practice-Related Reduction of Dual-Task Costs Under Conditions of a Manual-Pedal Response

Combination. *Journal of Cognitive Psychology*, *23*(1), 29–44. https://doi.org/10.1080/20445911.2011.448025

Liepelt, R., Strobach, T., Frensch, P., & Schubert, T. (2011). Improved Intertask Coordination After Extensive Dual-Task Practice. *Quarterly Journal of Experimental Psychology (2006)*, *64*(7), 1251–1272. https://doi.org/10.1080/17470218.2010.543284

Maquestiaux, F., Hartley, A. A., & Bertsch, J. (2004). Can Practice Overcome Age-Related Differences in the Psychological Refractory Period Effect? *Psychology and Aging*, *19*(4), 649–667. https://doi.org/10.1037/0882-7974.19.4.649

Maquestiaux, F., Laguë-Beauvais, M., Ruthruff, E., & Bherer, L. (2008). Bypassing the Central Bottleneck After Single-Task Practice in the Psychological Refractory Period Paradigm: Evidence for Task Automatization and Greedy Resource Recruitment. *Memory & Cognition*, *36*(7), 1262–1282. https://doi.org/10.3758/MC.36.7.1262

Maquestiaux, F., Ruthruff, E., Defer, A., & Ibrahime, S. (2018). Dual-Task Automatization: The Key Role of Sensory-Motor Modality Compatibility. *Attention, Perception & Psychophysics*, *80*(3), 752–772. https://doi.org/10.3758/s13414-017-1469-4

Mayr, U., & Kliegl, R. (2000). Task-Set Switching and Long-Term Memory Retrieval. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *26*(5), 1124–1140. https://doi.org/10.1037/0278-7393.26.5.1124

McIsaac, T. L., Lamberg, E. M., & Muratori, L. M. (2015). Building a Framework for a Dual Task Taxonomy. *BioMed Research International*, *2015*, 591475. https://doi.org/10.1155/2015/591475

Meyer, D. E., & Kieras, D. E. (1997a). A Computational Theory of Executive Cognitive Processes and Multiple-Task Performance: Part 2. Accounts of Psychological Refractory-Period Phenomena. *Psychological Review*, *104*(4), 749.

Meyer, D. E., & Kieras, D. E. (1997b). A Computational Theory of Executive Cognitive Processes and Multiple-Task Performance: Part I. Basic Mechanisms. *Psychological Review*, *104*(1), 3.

Miller, J., & Ulrich, R. (2008). Bimanual Response Grouping in Dual-Task Paradigms. *Quarterly Journal of Experimental Psychology*, *61*(7), 999–1019. https://doi.org/10.1080/17470210701434540

Monsell, S. (2003). Task Switching. *Trends in Cognitive Sciences*, *7*(3), 134–140. https://doi.org/10.1016/S1364-6613(03)00028-7

Musslick, S., & Cohen, J. D. (2021). Rationalizing Constraints on the Capacity for Cognitive Control. *Trends in Cognitive Sciences*, *25*(9), 757–775. https://doi.org/10.1016/j.tics.2021.06.001

Navon, D., & Miller, J. (2002). Queuing or Sharing? A Critical Evaluation of the Single-Bottleneck Notion. *Cognitive Psychology*, *44*(3), 193–251. https://doi.org/10.1006/cogp.2001.0767

Naylor, J. C., & Dickinson, T. L. (1969). Task Structure, Work Structure, and Team Performance. *Journal of Applied Psychology*, *53*(3, Pt.1), 167–177. https://doi.org/10.1037/h0027350

Norman, D. A., & Bobrow, D. G. (1975). On Data-Limited and Resource-Limited Processes. *Cognitive Psychology*, *7*(1), 44–64. https://doi.org/10.1016/0010-0285(75)90004-3

Oswald, F. L., Hambrick, D. Z., & Jones, A. L. (2007). Keeping All the Plates Spinning: Understanding and Predicting Multitasking Performance. In *Learning to Solve Complex Scientific Problems*. Routledge.

Pashler, H. (1984). Processing Stages in Overlapping Tasks: Evidence for a Central Bottleneck. *Journal of Experimental Psychology: Human Perception and Performance*, *10*(3), 358–377. https://doi.org/10.1037//0096-1523.10.3.358

Pashler, H. (1994). Dual-Task Interference in Simple Tasks: Data and Theory. *Psychological Bulletin*, *116*(2), 220–244. https://doi.org/10.1037/0033-2909.116.2.220

Pashler, H., & Christian, C. L. (1994). Bottlenecks in Planning and Producing Vocal, Manual and Foot Responses, 61.

Posner, M. I. (1980). Orienting of Attention. *Quarterly Journal of Experimental Psychology*, *32*(1), 3–25. https://doi.org/10.1080/00335558008248231

Redick, T. S., Shipstead, Z., Harrison, T. L., Hicks, K. L., Fried, D. E., Hambrick, D. Z., Kane, M. J., & Engle, R. W. (2013). No Evidence of Intelligence Improvement After Working Memory Training: A Randomized, Placebo-Controlled Study. *Journal of Experimental Psychology: General*, *142*(2), 359–379. https://doi.org/10.1037/a0029082

Redick, T. S., Shipstead, Z., Meier, M. E., Montroy, J. J., Hicks, K. L., Unsworth, N., Kane, M. J., Hambrick, D. Z., & Engle, R. W. (2016). Cognitive Predictors of a Common Multitasking Ability: Contributions From Working Memory, Attention Control, and Fluid Intelligence. *Journal of Experimental Psychology: General*, *145*(11), 1473–1492. https://doi.org/10.1037/xge0000219

Robinson, P. (2001). Task Complexity, Task Difficulty, and Task Production: Exploring Interactions in a Componential Framework. *Applied Linguistics*, *22*(1), 27–57. https://doi.org/10.1093/applin/22.1.27

Rubinstein, J. S., Meyer, D. E., & Evans, J. E. (2001). Executive Control of Cognitive Processes in Task Switching. *Journal of Experimental Psychology: Human Perception and Performance*, *27*(4), 763–797. https://doi.org/10.1037/0096-1523.27.4.763

Ruthruff, E., Pashler, H., & Klaassen, A. (2001). Processing Bottlenecks in Dual-Task Performance: Structural Limitation or Strategic Postponement? *Psychonomic Bulletin & Review*, *8*(1), 73–80. https://doi.org/10.3758/BF03196141

Ruthruff, E., Pashler, H. E., & Hazeltine, E. (2003). Dual-Task Interference With Equal Task Emphasis: Graded Capacity Sharing or Central Postponement? *Perception & Psychophysics*, *65*(5), 801–816. https://doi.org/10.3758/bf03194816

Ruthruff, E., van Selst, M., Johnston, J. C., & Remington, R. (2006). How Does Practice Reduce Dual-Task Interference: Integration, Automatization, or Just Stage-Shortening? *Psychological Research*, *70*(2), 125–142. https://doi.org/10.1007/s00426-004-0192-7

Salvucci, D. D., Taatgen, N. A., & Borst, J. P. (2009). Toward a Unified Theory of the Multitasking Continuum: From Concurrent Performance to Task Switching, Interruption, and Resumption.

Santiago-Espada, Y., Myer, R. R., Latorella, K. A., & Comstock, J. R. (2011). The Multi-Attribute Task Battery II (MATB-II) Software for Human Performance and Workload Research: A User's Guide, 269.

Schneider, W., & Shiffrin, R. M. (1977). Controlled and Automatic Human Information Processing: I. Detection, Search, and Attention. *Psychological Review*, *84*(1), 1–66. https://doi.org/10.1037/0033-295X.84.1.1

Schubert, T., Fischer, R., & Stelzel, C. (2008). Response Activation in Overlapping Tasks and the Response-Selection Bottleneck. *Journal of Experimental Psychology. Human Perception and Performance*, *34*(2), 376–397. https://doi.org/10.1037/0096-1523.34.2.376

Schubert, T., Kübler, S., & Strobach, T. (2024). A Mechanism Underlying Improved Dual-Task Performance After Practice: Reviewing Evidence for the Memory Hypothesis. *Psychonomic Bulletin & Review*. https://doi.org/10.3758/s13423-024-02498-0

Schubert, T., Liepelt, R., Kübler, S., & Strobach, T. (2017). Transferability of Dual-Task Coordination Skills After Practice With Changing Component Tasks. *Frontiers in Psychology*, *8*, 956. https://doi.org/10.3389/fpsyg.2017.00956

Schubert, T., & Strobach, T. (2018). Practice-Related Optimization of Dual-Task Performance: Efficient Task Instantiation During Overlapping Task Processing. *Journal of Experimental Psychology: Human Perception and Performance*, *44*(12), 1884–1904. https://doi.org/10.1037/xhp0000576

Schumacher, E. H., & Hazeltine, E. (2016). Hierarchical Task Representation: Task Files and Response Selection. *Current Directions in Psychological Science*, *25*(6), 449–454. https://doi.org/10.1177/0963721416665085

Schumacher, E. H., Seymour, T. L., Glass, J. M., Fencsik, D. E., Lauber, E. J., Kieras, D. E., & Meyer, D. E. (2001). Virtually Perfect Time Sharing in Dual-Task Performance: Uncorking the Central Cognitive Bottleneck. *Psychological Science*, *12*(2), 101–108. https://doi.org/10.1111/1467-9280.00318

Seibel, R. (1963). Discrimination Reaction Time for a 1,023-Alternative Task. *Journal of Experimental Psychology*, *66*(3), 215–226. https://doi.org/10.1037/h0048914

Seow, S. (2005). Information Theoretic Models of HCI: A Comparison of the Hick-Hyman Law and Fitts' Law. *Human-Computer Interaction*, *20*(3), 315–352. https://doi.org/10.1207/s15327051hci2003_3

Sigman, M., & Dehaene, S. (2008). Brain Mechanisms of Serial and Parallel Processing During Dual-Task Performance. *The Journal of Neuroscience : The Official Journal of the Society for Neuroscience*, *28*(30), 7585–7598. https://doi.org/10.1523/JNEUROSCI.0948-08.2008

Stefani, M., Sauter, M., Eichert, F., & Mack, W. (2022). Expanding Dual-Task Research by a Triple-Task. *Open Psychology*, *4*(1), 152–174. https://doi.org/10.1515/psych-2022-0008

Stefani, M., Sauter, M., & Mack, W. (under Review). Multi-tasking Costs in Triple-Task Performance Despite Dualtask Preparation. *Memory & Cognition.*

Stelzel, C., Brandt, S. A., & Schubert, T. (2009). Neural Mechanisms of Concurrent Stimulus Processing in Dual Tasks. *NeuroImage*, *48*(1), 237–248. https://doi.org/10.1016/j.neuroimage.2009.06.064

Stelzel, C., Schumacher, E. H., Schubert, T., & D'Esposito, M. (2006). The Neural Effect of Stimulus-Response Modality Compatibility on Dual-Task Performance: An fMRI Study. *Psychological Research*, *70*(6), 514–525. https://doi.org/10.1007/s00426-005-0013-7

Strobach, T. (2019). The Dual-Task Practice Advantage: Empirical Evidence and Cognitive Mechanisms. *Psychonomic Bulletin & Review.* https://doi.org/10.3758/s13423-019-01619-4

Strobach, T. (2023). Cognitive Control and Meta-Control in Dual-Task Coordination. *Psychonomic Bulletin & Review.* https://doi.org/10.3758/s13423-023-02427-7

Strobach, T., Frensch, P., Mueller, H. J., & Schubert, T. (2012). Testing the Limits of Optimizing Dual-Task Performance in Younger and Older Adults. *Frontiers in Human Neuroscience*, *6.* https://doi.org/10.3389/fnhum.2012.00039

Strobach, T., Frensch, P., Müller, H., & Schubert, T. (2012). Age- And Practice-Related Influences on Dual-Task Costs and Compensation Mechanisms Under Optimal Conditions of Dual-Task Performance. *Aging, Neuropsychology, and Cognition*, *19*(1-2), 222–247. https://doi.org/10.1080/13825585.2011.630973

Strobach, T., Frensch, P. A., Soutschek, A., & Schubert, T. (2012). Investigation on the Improvement and Transfer of Dual-Task Coordination Skills. *Psychological Research*, *76*(6), 794–811. https://doi.org/10.1007/s00426-011-0381-0

Strobach, T., Liepelt, R., Pashler, H., Frensch, P. A., & Schubert, T. (2013). Effects of Extensive Dual-Task Practice on Processing Stages in Simultaneous Choice Tasks. *Attention, Perception & Psychophysics*, *75*(5), 900–920. https://doi.org/10.3758/s13414-013-0451-z

Strobach, T., Liepelt, R., Schubert, T., & Kiesel, A. (2012). Task Switching: Effects of Practice on Switch and Mixing Costs. *Psychological Research*, *76*(1), 74–83. https://doi.org/10.1007/s00426-011-0323-x

Strobach, T., Salminen, T., Karbach, J., & Schubert, T. (2014). Practice-Related Optimization and Transfer of Executive Functions: A General Review and a Specific Realization of Their Mechanisms in Dual Tasks. *Psychological Research*, *78*(6), 836–851. https://doi.org/10.1007/s00426-014-0563-7

Strobach, T., & Schubert, T. (2017). Mechanisms of Practice-Related Reductions of Dual-Task Interference With Simple Tasks: Data and Theory. *Advances in Cognitive Psychology*, *13*(1), 28–41. https://doi.org/10.5709/acp-0204-7

Stroop, J. R. (1935). Studies of Interference in Serial Verbal Reactions. *Journal of Experimental Psychology*, *18*(6), 643–662.

Telford, C. W. (1931). The Refractory Phase of Voluntary and Associative Responses. *Journal of Experimental Psychology*, *14*(1), 1.

Tombu, M., & Jolicoeur, P. (2004). Virtually No Evidence for Virtually Perfect Time-Sharing. *Journal of Experimental Psychology. Human Perception and Performance*, *30*(5), 795–810. https://doi.org/10.1037/0096-1523.30.5.795

Tombu, M., & Jolicøeur, P. (2003). A Central Capacity Sharing Model of Dual-Task Performance. *Journal of Experimental Psychology: Human Perception and Performance*, *29*(1), 3–18. https://doi.org/10.1037/0096-1523.29.1.3

Treisman, A. M., & Gelade, G. (1980). A Feature-Integration Theory of Attention. *Cognitive Psychology*, *12*(1), 97–136. https://doi.org/10.1016/0010-0285(80)90005-5

Ulrich, R., Fernández, S. R., Jentzsch, I., Rolke, B., Schröter, H., & Leuthold, H. (2006). Motor Limitation in Dual-Task Processing Under Ballistic Movement Conditions. *Psychological Science*, *17*(9), 788–793. https://doi.org/10.1111/j.1467-9280.2006.01783.x

Welford, A. T. (1952). The Psychological Refractory Period and the Timing of High-Speed Performance - A Review and a Theory. *British Journal of Psychology*, *43*(1), 2.

Wickens, C. D. (2002). Multiple Resources and Performance Prediction. *Theoretical Issues in Ergonomics Science*, *3*(2), 159–177. https://doi.org/10.1080/14639220210123806

Wickens, C. D. (2008). Multiple Resources and Mental Workload. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, *50*(3), 449–455. https://doi.org/10.1518/001872008X288394

Wickens, C. D., & Liu, Y. (1988). Codes and Modalities in Multiple Resources: A Success and a Qualification. *Human Factors*, *30*(5), 599–616. https://doi.org/10.1177/001872088803000505

Wood, R. E. (1986). Task Complexity: Definition of the Construct. *Organizational Behavior and Human Decision Processes*, *37*(1), 60–82. https://doi.org/10.1016/0749-5978(86)90044-0

Wood, R. E., Mento, A. J., & Locke, E. A. (1987). Task Complexity as a Moderator of Goal Effects: A Meta-Analysis. *Journal of Applied Psychology*, *72*(3), 416–425. https://doi.org/10.1037/0021-9010.72.3.416

Zacher, H., & Frese, M. (2018). The SAGE Handbook of Industrial, Work & Organizational Psychology. In *The SAGE Handbook of Industrial, Work & Organizational Psychology* (pp. 122–143). SAGE Publications Ltd. https://doi.org/10.4135/9781473914957