The Impact of Dual-Tasking on Sequence Learning

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Christina Pfeifer

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Dean:

Univ.-Prof. Dr. Peter Loos

Saarland University, Germany

Principal Advisor:

Univ.- Prof. Dr. phil. habil. Stefan Panzer

Saarland University, Germany

Second Advisor:

Prof. Dr. Roland Thomaschke

Albert-Ludwigs-University Freiburg, Germany

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Abstract

Movement sequences are crucial in our daily routines, such as tying our shoes, signing our names, or playing the piano. We typically execute these movement sequences in conjunction with other tasks. For instance, we might drink a cup of coffee while listening to the news or compose a text message while talking to a friend. We can sometimes successfully execute both tasks simultaneously without any performance detriment. However, there are instances when we fail, and either one or both tasks suffer. This dissertation investigates the impact of dual-tasking on movement sequence learning. The movement sequences consisted of flexion-extension movements of the elbow. Specifically, two distinct types of movement sequence tasks are employed: a 16-element task and a continuous sequence task. The 16-element task is used to examine the stability of a response structure against a dual-task, and the continuous sequence task is used to investigate the attention demands of sequence representations. The following experiments were conducted to accomplish the research objectives: First, the impact of a dual-task on the response structure (16-element task) was investigated. Second, the effect of multiple days of single-task practice on the attentional demands of sequence representations (continuous sequence task) was examined. Third, the impact of dual-task practice on the shift of attentional demands of sequence representations (continuous sequence task) was examined. According to the results, the response structure of the 16-element task showed partial stability against the secondary task. The secondary task did not affect the element duration. However, the zero crossings increased during the transition from one subsequence to another in the dual-task situation (Experiment 1). For the continuous sequence task, attention is required by the motor and visual-spatial sequence representation, regardless of the number of single-task practice sessions. During an early practice stage, the visual-spatial representation was vulnerable to a secondary task (Experiment 2). The attentional demands of the visual-spatial and motor representations were unaffected by dual-task practice. Attentional demands were higher at the beginning than at the middle and the end of the movement execution (Experiment 3).

Zusammenfassung

Bewegungssequenzen sind entscheidend für unsere täglichen Routinen, wie das Binden unserer Schuhe, das Unterschreiben unseres Namens oder das Klavierspielen. In der Regel führen wir diese Bewegungssequenzen in Verbindung mit anderen Aufgaben aus. So trinken wir eine Tasse Kaffee, während wir uns die Nachrichten im Radio anhören, oder wir verfassen eine Textnachricht, während wir mit einem Freund sprechen. Manchmal gelingt es uns, beide Aufgaben gleichzeitig auszuführen, ohne dass die Leistung darunter leidet. Es gibt jedoch auch Fälle, in denen wir versagen und entweder eine oder beide Aufgaben darunter leiden. Diese Dissertation befasst sich mit den Auswirkungen von Doppeltätigkeiten beim Lernen von Bewegungssequenzen. Die Bewegungssequenzen bestanden aus Flexions- und Extensionsbewegungen des Ellenbogengelenks. Es werden zwei unterschiedliche Sequenzaufgaben verwendet, die 16-Elementen Aufgabe und die kontinuierliche Sequenzaufgabe. Mithilfe der 16-Elementen Aufgabe wird die Stabilität einer Sequenzstruktur gegen eine Zweitaufgabe untersucht, wobei die kontinuierliche Sequenzaufgabe die Aufmerksamkeitsanforderungen der Sequenzrepräsentationen untersucht. Es wurden folgende Experimente durchgeführt: Das erste Experiment untersucht den Einfluss einer Doppelaufgabe auf die Sequenzstruktur (16-Elementen Aufgabe). Das zweite Experiment prüft die Auswirkung einer ausgedehnten Single-Task-Übungsphase auf die Aufmerksamkeitsanforderungen von Sequenzrepräsentationen (kontinuierliche Sequenzaufgabe). Das dritte Experiment analysiert den Einfluss von Dual-Task-Übung auf die Verschiebung der Aufmerksamkeitsanforderungen von Sequenzrepräsentationen (kontinuierliche Sequenzaufgabe). Die Ergebnisse zeigen, dass die Sequenzstruktur der 16-Elementen Aufgabe gegenüber der Sekundäraufgabe teilweise stabil ist. Die Sekundäraufgabe hatte keinen Einfluss auf die Zeitspanne, die benötigt wird, um von einem Zielelement zum nächsten zu gelangen (E*lement Duration*).

Allerdings stiegen die Nulldurchgänge (*Zero Crossings*) beim Übergang von einer Teilsequenz zur nächsten in der Dual-Task-Situation an (Experiment 1). Die Aufmerksamkeit wird von der motorischen und visuell-räumlichen Sequenzrepräsentation beansprucht, unabhängig von der Anzahl der Single-Task-Übungstage. Während der frühen Übungsphase war die visuell-räumliche Repräsentation anfällig für eine Sekundäraufgabe (Experiment 2). Die Aufmerksamkeitsanforderungen der visuell-räumlichen und der motorischen Repräsentation wurden durch die Dual-Task-Übung nicht beeinflusst. Die Aufmerksamkeitsanforderungen waren zu Beginn höher als in der Mitte und am Ende der Bewegungsausführung (Experiment 3).

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1 Introduction

Movement sequences play an essential role in our everyday life. For example, we sequence movements when we type on the keyboard, drink coffee, play the piano, or drive a car. For instance, drinking coffee requires linking a series of movements. These distinct subsequences comprise (1) reaching for the cup and coffee pot, (2) pouring in the coffee, (3) grabbing the cup, (4) lifting it to the mouth, (5) tilting it, and (6) drinking from it. Specifically, when we perform movements for the first time, they tend to be performed discretely and inconsistently. However, with repeated practice, these movements become more fluid, faster, and smoother, and often, they are executed without requiring notable attention and at the same time with other tasks.

Movement sequence learning has been a major area of interest in motor learning and control for several decades, as evidenced by numerous studies or reviews (Clegg et al., 1998; Dean et al., 2008; Massing et al., 2018; Panzer & Shea, 2008; Shea et al., 2011; Verwey, 2001; Wilde et al., 2005; Willingham, 1998; Willingham et al., 2000). The beginning of the research field started with Lashley's (1951) pioneering research on the serial order of behavior, which raised interest in sequence learning research. Lashley (1951) proposed that hierarchically organized central plans govern sequential movements. Rosenbaum and colleagues (1983) further developed this concept, describing the hierarchical control of movement sequences as a tree-traversal process. Higher-level nodes process sequence information and branch to lower-level nodes where specific element and effector information is stored (Shea et al., 2016). Povel and Collard (1982) also discussed this process. Therefore, it has been suggested that sequences are not only hierarchically structured but also executed by that hierarchy. This concept was found to reasonably represent some of the temporal delays (latency and errors increase as more nodes need to be traversed) in the execution of individual elements in the sequence, as well as the grouped elements (Shea et al., 2016).

In the realm of theoretical models for sequence learning, Verwey (2001) proposed a dual processor model (DPM) consisting of a cognitive and a motor processor for executing sequences. The cognitive processor represents information related to the order and organization of elements in the sequence (Shea et al., 2016; Verwey, 2001). In contrast, the motor processor contains information on the selection and activation patterns of various effectors required to execute the movement sequence. The main difference between the DPM and earlier hierarchical models is that the former posits two distinct processing systems, whereas the latter assumes a single processing system that traverses a hierarchical sequence representation and executes each element immediately upon retrieval (Verwey, 2001).

In sequence learning experiments, researchers frequently employ key-pressing tasks in which participants are prompted by a visual cue to press the corresponding key in a repeated order (Krakauer et al., 2019; Nissen & Bullemer, 1987; Verwey, 2001). As participants gain practice, they become more proficient in anticipating the following response, reducing their dependence on the visually presented stimulus, which in turn leads to reduced response times (Vieluf et al., 2015). These reduced response times can be theoretically explained by the process of chunking. Initially independently composed elements of the sequence are later grouped through practice, forming what are known as motor chunks (Verwey, 2001) or subsequences (Kovacs, Muehlbauer, et al., 2009). The manner in which the elements were divided into subsequences and subsequently concatenated with one another was designated as the sequence response structure (Dean et al., 2008; Panzer & Shea, 2008; Povel & Collard, 1982). This sequence response structure is thought to decrease the processing and cognitive demands (Shea et al., 2011).

Another perspective on sequence learning is presented in the parallel neural network model proposed by Hikosaka et al. (1999) and it determines the development of sequence representations. This theoretical framework is based on results obtained from a multi-element sequential key-pressing task, the *m x n* task. This task requires *n* sets of *m* button presses presented on a 3 x 3 grid (Bapi et al., 2000; Hikosaka et al., 1999). For example, the 2 x 5 task was used for monkeys, and the 2 x 10 task was primarily used for human participants (Bapi et al., 2000; Hikosaka et al., 1999). The 2 x 10 task requires two button presses for ten consecutive trials (Bapi et al., 2000). Two transfer tests were introduced to disentangle the two sequence representations. For this a visual test with the same visual-spatial location of the illuminated targets and a motor test with the same finger movements are required as during the acquisition phase (Bapi et al., 2000). The results indicated that sequence learning occurs independently and in parallel in two learning systems, one encodes the movement in visual-spatial coordinates (e.g., target locations) at an early stage of practice, and the other in motor coordinates (joint angles, muscle activation patterns) at a later stage of practice (Hikosaka et al., 1999, 2002).

The majority of sequence learning experiments use key-pressing tasks (Bapi et al., 2000; Hikosaka et al., 1999, 2002; Verwey, 1995), which provide a cognitive understanding of how humans process information as the motor demands of these key-pressing tasks are reduced (Shea et al., 2011). However, the results of these approaches are constrained to the response times of the key-pressing tasks (Shea et al., 2011). Inspired by the key-pressing tasks, in recent research more dynamic arm-movement sequence tasks have been developed, with a more balanced combination of visual-spatial and motor codes (Kovacs, Han, et al., 2009; Kovacs, Muehlbauer, et al., 2009; Leinen et al., 2015; Massing et al., 2018; Park & Shea, 2005). Two types of dynamic arm-movement sequence tasks have been evolved: the multiple-element sequence task (Muehlbauer et al., 2007; Park & Shea, 2005; Shea et al., 2011) and the continuous sequence task (Kovacs, Han, et al., 2009; Leinen et al., 2015). A sequential movement of extending and flexing the elbow using a limb-lever system is common to both tasks. The multiple-element sequence task and the continuous sequence task address some of the same, but also different, concepts of sequential learning.

The multiple-element task comprises a number of elements presented in a specific order. Therefore, for example, a 16-element task requires participants to aim at 16 target elements in the correct order. The 16-element task closely resembles the classic key-pressing tasks. An illuminated target indicates to participants to move the lever to that target position. If a target is missed, it remains illuminated until the participant returns the lever to the target position. In previous research using the multiple-element sequence task (Kovacs, Muehlbauer, et al., 2009; Park & Shea, 2005; Shea et al., 2011 for a review) it has been revealed that participants impose a response structure on the movement sequence consisting of a series of motor chunks (Shea et al., 2011). These independent motor chunks are concatenated and may be refined through a process that is known as "coarticulation" or "dynamic optimization" (Jordan, 1995), resulting in an overall movement sequence response structure (Braden et al., 2008). Accordingly, the 16-element task is suitable for studying the development of a movement sequence response structure (Kovacs, Muehlbauer, et al., 2009; Park & Shea, 2005; Shea et al., 2016).

The continuous sequence task requires participants to trace a goal-movement pattern with three or five reversal points as closely as possible. In research using the continuous sequence task the development of sequence representation was investigated, and attempts made to dissociate pre-plan and online control processes by manipulating the concurrent visual feedback (Kovacs, Han, et al., 2009; Leinen et al., 2015; Shea et al., 2011). The visual-spatial codes entail the location of the target movement, and the motor codes involve precise control of agonist and antagonist muscles to reach the target positions. In conclusion, both dynamic arm-movement sequence tasks involve similar performance measures as the key-pressing tasks, such as the response time, but also expand the performance measures by dynamical factors such as the displacement, velocity, and acceleration of the movement (Boutin et al., 2010).

In our everyday lives, it is common to execute multiple tasks simultaneously. Therefore, dual-tasking plays a significant role in the worlds of work and sports. For instance, a call center employee is expected to talk to a customer on the phone and simultaneously type on a computer keyboard, looking for information to help the customer. A cyclist in a competition receives information about possible race tactics or current attacks of an opposing team via an in-ear communication system while riding at speeds of over 40 km/h in the peloton. These examples demonstrate that performing two tasks concurrently in specific situations does not necessarily lead to an externally visible/ measurable decline in performance. However, we have all encountered difficulties in our dual-tasking abilities when we, for instance, have tried to speak and write simultaneously.

In order to assess the attention demands of a task, the dual-task technique is commonly used. This approach combines a primary task, usually the task of interest, with a secondary task. Thus, two types of secondary tasks can be applied to investigate the attention demands of the task of interest: a continuous secondary task, such as a tone-counting task, or a discrete secondary task, such as a probe task (Goh et al., 2014; Magill & Anderson, 2017). A continuous secondary task is often selected to evaluate the extent of interference. In this case it is assumed that the attention demands of the primary task remain stable; thus, a continuous secondary task produces constant interference. Therefore, comparing single-task and dual-task performance of the primary task is crucial to investigate the resistance to dual-task interferences (Goh et al., 2012). Reduced attention is inferred by the performance of the primary task in a single-task and dual-task situation. When no performance differences are observed between the single-task and dual-task situations, it is assumed that the primary task is resistant to dual-task interferences and requires less attention. Limitations of this approach include the inability to conduct specific analysis at certain points during the primary task and the need for continuous secondary tasks, such as tone-counting tasks or n-back tasks, to load the working memory (Esmaeili Bijarsari, 2021).

A temporary analysis of attention demands can be achieved through a probe task (Ells, 1973; Wilke & Vaughn, 1976; Woollacott & Shumway-Cook, 2002). Its use is based on the assumption that attention is fixed in capacity (Magill & Anderson, 2017; Woollacott & Shumway-Cook, 2002) and fluctuates throughout the movement. The probe paradigm requires a comparison of the single-task and dual-task performance of the secondary task to derive the attention demands of the primary task (Magill & Anderson, 2017). Therefore, if the primary task requires attention, the performance of the secondary task will be worse when performed simultaneously with the primary task than when performed alone (Magill & Anderson, 2017). On the contrary, if attention can be divided for both tasks, the performance of the secondary task should be similar in a single-task and dual-task situation. The probe task offers the possibility to analyze the temporal change in attention demands. However, it is important to consider the use of a few experimental controls when using this task, such as inserting catch trials and taking a baseline measurement at the beginning of practice (Goh et al., 2014).

This dissertation contributes to the theoretical understanding of human dual-tasking from the cognitive flexibility and cognitive plasticity perspective (Koch et al., 2018). Research referring to cognitive flexibility comprises, for instance, of the investigation of the mechanisms of central capacity sharing (Koch et al., 2018). Therefore, the success or failure of simultaneous task execution depends on the flexible sharing of either a general (Kahneman, 1973) or modality-specific capacity (Wickens, 1984). The research done for this dissertation employed the capacity-sharing model approach to investigate dual-task performance. Furthermore, cognitive plasticity was also an important perspective for this research. Plasticity is generally used to describe modifications of cognitive processes as a result of practice (Koch et al., 2018). The experiments undertaken for this work involved the examination of the impact of various practice conditions on dual-task performance.

In detail, the work for this dissertation involved an examination of the impact of dual-tasking on movement sequence learning. In particular, on the response structure and the sequence representations. Moreover, for this dissertation an investigation was made of dynamic arm-movements, demonstrating how the theoretical concepts developed in the key-pressing task study can be applied to dynamic arm-movement sequence tasks. In Experiment 1, the dual-task was used to investigate the impact of an auditory secondary task on an already learned movement sequence. The movement sequence task was a 16-element task, where participants had to move the lever from one illuminated target to the next. The acquisition of the 16-element task was under single-task condition. The secondary task, a simple reaction time task, was triggered by the 7th and 12th element of the movement sequence during the transfer tests.

In experiments 2 and 3, the task was changed to the continuous sequence task, where participants had to trace a criterion target waveform. This continuous sequence task was used to examine the development of sequence representations. Combining the inter-manual transfer design with the dual-task methodology enabled an investigation of the attentional requirements of the movement sequence representations. Prior to executing the task, participants were displayed the criterion waveform and the position of the limb (cursor). However, as soon as they initiated the movement, the criterion waveform and the cursor disappeared. The probe task was triggered by the first, third, or fifth reversal points of the sequence during each trial.

2 Theoretical Background and Research Interests

This chapter contains a summary of the existing research and accompanying theoretical background for the primary research domain. In Chapter 2.1 an outline is presented of the theoretical models about attention, such as the single-channel, limited capacity, and multiple resource models. The emergence of dual-task interferences is further embedded with consideration given to the theoretical approaches. In addition, the prevailing dual-task paradigms are described and were used to analyze the processing and attention demands of processes involved in movement sequence learning.

In Chapter 2.2 focus is placed on the emergence of a response structure, including chunking and concatenating individual subsequences. Finally, the chapter contains a discussion on the application of dynamic arm-movement sequences in the context of the movement sequence organization.

In Chapter 2.3 another theoretical framework is discussed of sequence learning that involves consideration of the development of sequence representations based on the encoding of the movement sequence. The codes and several characteristics that contribute to the development of these sequence representations are presented.

2.1 Attention and Dual-Tasking

Dual-tasking is a common occurrence in our daily lives. However, concurrently performing two tasks can negatively affect performance (Nissen & Bullemer, 1987; Schumacher & Schwarb, 2009; Stets et al., 2020; Strayer & Johnston, 2001). Dual-tasking is defined as cognitive processes that overlap in time and belong to at least two different tasks (Koch et al., 2018; Poljac et al., 2018). For decades, researchers have extensively studied dual-tasking and the associated costs (Allport et al., 1972; Pashler, 1994; Strobach, 2020) to gain insight into the cognitive structures of the human information processing system (Koch et al., 2018). Based on the results, dual-task interferences can be described by three main theoretical assumptions: the single-channel model (Welford, 1952) and its modifications (Broadbent, 1958; Deutsch & Deutsch, 1963; Treisman, 1964), the limited central capacity (Kahneman, 1973), and multiple resources (Wickens, 1984).

The single-channel model and central capacity model are conceptually very similar but differ in some aspects (Heuer, 1996). Both models share the commonality that tasks impose demands on a central entity, and competition for that entity represents a cause of dual-task interference (Heuer, 1996). Depending on the theoretical approach, this central entity is defined as a single channel (Welford, 1952) or as capacity (Kahneman, 1973). The single-channel model (Welford, 1952), the filter theory (Broadbent, 1958), and its modifications (Deutsch & Deutsch, 1963; Treisman, 1964), are associated with less flexible information processing and a structural limitation such as a filter or a bottleneck (Broadbent, 1958, Welford, 1952) at various stages of human information processing. The single-channel model (Welford, 1952) posits that attention is required at all stages of information processing, allowing only serial processing of one single stimulus. According to this model, the allocation of the central entity is only possible on an all-or-none basis. Therefore, interference occurs whenever a simultaneous secondary task is introduced.

Theories such as Broadbent's (1958) and its modifications by Deutsch and Deutsch (1963), as well as that of Treisman (1964), suggest that not all stages of processing require attention. According to these theories, a filter selects information either at an early stage (Broadbent, 1958) or a later stage of processing (Deutsch & Deutsch, 1963; Treisman, 1964), which allows for parallel processing before the 'filter' is encountered and serial processing after the 'filter.' The experimental evidence of serial and discrete cognitive processing has been included in the Psychological Refractory Period (PRP) paradigm (Telford, 1931; Welford, 1952). Telford (1931) ascertained that when two stimuli are presented in rapid succession, the response to the second stimulus is postponed (PRP effect). Therefore, dual-task interference depends on the temporal overlap of two tasks, with a small interval between them, known as Stimulus Onset Asynchrony (SOA), resulting in a significantly slower reaction time to the second stimulus (Pashler, 1994). This effect provides insight into the processing of the second stimulus when the processing of the first stimulus is still ongoing (Schmidt et al., 2018). Accordingly, the magnitude of dual-task interference depends on the duration of the SOA.

The location of the bottleneck has been altered from a bottleneck in perception to a bottleneck in the central stage by consistent use of the PRP paradigm for various applications (Koch et al., 2018). One premise related to the application of the PRP paradigm is the use of different stimulus modalities for perception and response, which reduces structural dual-task interferences (Koch et al., 2018). Therefore, any remaining dual-task cost can be assigned to the central processing stage which corresponds to the decision and response selection processes (Koch et al., 2018; Pashler, 1994). This central stage is predicted to have limited capacity, thereby preventing the simultaneous processing of two stimuli. This suggests that parallel processing can only occur at the perceptual and motor levels (Koch et al., 2018; Pashler, 1994). Another influential theoretical approach ‘limited central capacity’ suggested by Kahneman (1973) allows for a graded allocation of the central entity to concurrent tasks (see Figure 1). This central entity is also referred to as attention or as mental effort (Kahneman, 1973). Kahneman (1973) has argued that attention is fixed and limited in capacity; however, this capacity could change as the task requirements alter. Therefore, this capacity can be freely allocated between concurrent tasks. According to this model, the extent of dual-task interferences depends on the exceeding of the limited capacity available or the allocation policy that distributes attention to the tasks (Kahneman, 1973). Therefore, several dual-task studies have been based on the theoretical background of Kahneman's capacity model (Allport et al., 1972; Bayot et al., 2018; Koch et al., 2018; Spelke et al., 1976). In particular, in earlier studies the possibility was advocated of dividing or allocating attention to concurrent tasks (Allport et al., 1972; Spelke et al., 1976). For example, Spelke et al., (1976) asked participants to read short stories while writing a list of dictated words. Following extensive practice, the participants were able to write the words, identify relationships between the dictated words, and categorize words with regard to meaning while reading at their normal speed. Kahneman's model (1973) and the evidence derived from it, lead to the argument that parallel processing could operate at all stages of processing but with some requirement for attention at the same time. However, it is crucial to view this central capacity model critically since the

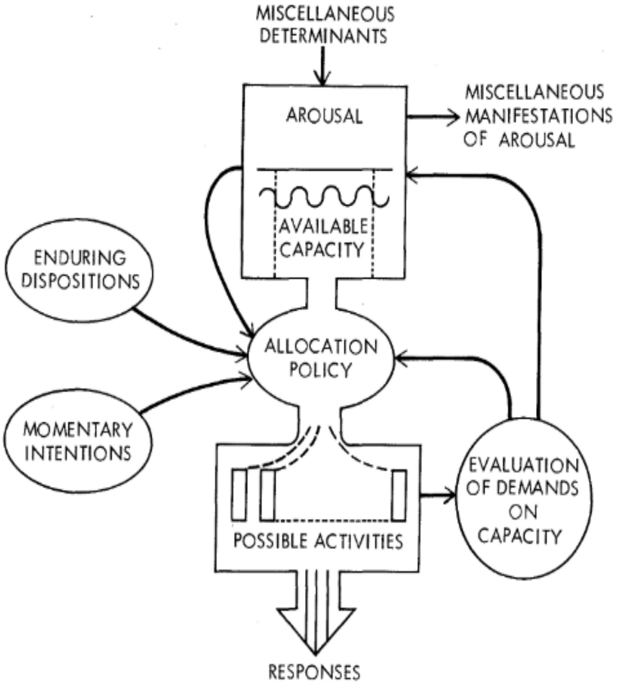

Figure 1. The capacity model for attention by Kahneman (1973)

construct of 'capacity' or 'attention' cannot be directly measured. The utilization of limited capacity is only determined by performance or loss of performance in a dual-task situation (Neumann, 1992). Moreover, the relationship between the independent variable (capacity) and the dependent variable (performance) is circular, as the independent variable is only anchored in the dependent variable (Neumann, 1992).

The capacity model proposed by Kahneman (1973) was later expanded upon by Wickens (1984, 2002) with the introduction of the multiple resource model. This model involves the existence of multiple resource pools, each with a limited capacity (Heuer, 1996; Navon & Gopher, 1979; Wickens, 1984, 2002). Empirical evidence indicates that dual-task interferences increase when tasks are structurally similar, particularly when they involve the same processor/stores (Allport et al., 1972), in comparison to when both tasks involve different processors/stores. In order to expand the concept of task similarity, combinations of stimulus modalities, task-specific processing codes and output modalities were further considered (Koch et al., 2018; Wickens 1984). It is therefore proposed that dual-task interference can also be described using a multiple resource approach to categorize the related modality-specific interferences. Wickens' (2002) multiple resource model encompasses four dimensions of human information processing including processing stages (perceptual/cognitive), sensory modalities (auditory/ visual), memory codes (visual/spatial), and response outputs (manual/ vocal) (see Figure 2). The magnitude of dual-task interferences can be derived from the four-dimensional resource model if the combined tasks occupy the same level of the dimensions (Wickens, 2002). Notably, it has been demonstrated that dual-task interferences are reduced when visual-manual and auditory-vocal modalities are combined, in comparison to other modality mappings such as visual-vocal or auditory-manual (Hazeltine et al., 2006; Koch et al., 2018).

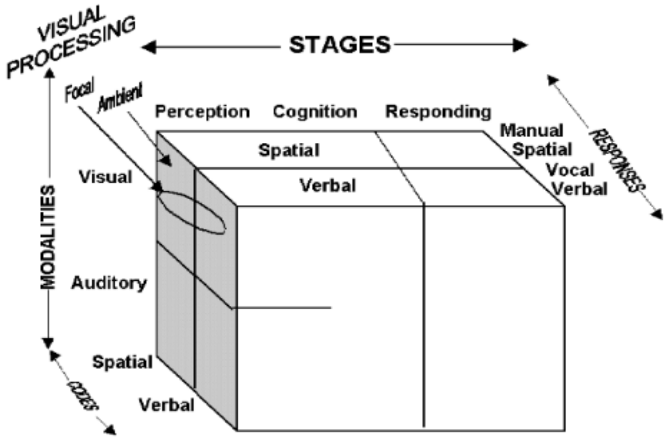

Figure 2. Structure of the multiple resource model (Wickens, 2002)

Both time-sharing and capacity-sharing approaches involve assumptions about the cognitive structure of the human information processing system. The former approach posits the existence of a limited central capacity, while the latter suggests the structural impossibility of processing two stimuli simultaneously through a single channel (i.e., bottleneck) during human information processing. However, capacity sharing can also be applied to the single-channel model by arguing that the central processing contains a structurally limited capacity (Koch et al., 2018). The distribution of capacity can be flexible and graded rather than available in an all-or-none manner (Koch et al., 2018; Tombu & Jolicoæur, 2003). Therefore, time-sharing models can be considered a specific variant of capacity-sharing models. This indicates that capacity-sharing models encompass a more general class of models (Koch et al., 2018).

The central capacity approach does not take into account structural interference as a cause of dual-task interferences (Koch et al., 2018; Neumann, 1992). Several empirical findings related to further dual-task interferences have led to assumptions being made about the existence of more specific resource. Thus, the more precisely the interference is analyzed, the more specific the resources can be postulated. However, postulating the existence of more resources does not yield any gain in knowledge, as they cannot be precisely identified (Neumann, 1992).

Despite some reservations, the limited central capacity approach has been well-established in dual-task research (Heuer, 1996; Koch et al., 2018; Navon & Gopher, 1979; Neumann, 1996; Tombu & Jolicoæur, 2003; Wollesen & Voelcker-Rehage, 2014; Yang et al., 2007). As there is no direct measure of attention, attention is instead inferred from the performance of the task of interest. A main approach used to investigate attention is the dual-task probe paradigm (Goh et al., 2014). In the dual-task probe paradigm, the attentional demands of the primary task are derived from the performance of the secondary probe task. Therefore, a decrease in reaction times to the probe stimulus indicates a reduction in attentional demands. The probe technique further allows a detailed analysis to be made of attentional demands at specific temporal loci (Kerr, 1975; Salmoni et al., 1976), leading to an understanding of the allocation of attention during movement execution. In previous studies using the probe technique to evaluate attentional demands an examination has been made of distinct motor tasks such as postural control and gait (Woollacott & Shumway-Cook, 2002), lever rotations (Ells, 1973), coincident timing task (Wrisberg & Shea, 1978), and dart throws (Wilke & Vaughn, 1976). Goh et al. (2014) has outlined a few experimental controls to be considered when applying the probe paradigm. First, catch trials should be included to prevent individuals from anticipating the probe tone. This will help to avoid any potential influence on reaction times and attention demands. Second, the sensitivity of the probe task should remain throughout the experiment to address the shift of attention demands (Goh et al., 2014). Third, a baseline measure of the probe task is required to determine the probe task performance (Goh et al., 2014). When using a dual-task probe paradigm in motor learning studies, it is essential to systematically examine these factors to ensure accurate interpretability of the findings.

2.2 Sequence Learning and the Response Structure: The 16-Element Task

How our brain represents, structures and processes movement sequences has been an important area of motor control and learning (Hikosaka et al., 1999; Keele et al., 1995, 2003; Verwey, 2001). Numerous theoretical models have resulted from research on movement sequence learning (Hikosaka et al., 1999; Keele et al., 1995; Verwey, 1995). According to Keele et al. (1995), movement sequences are processed by two independent processing modules. One of these (cognitive module) organizes and plans the sequence elements, while the other (motor module) selects specific effectors and activation patterns for executing the movement. In a similar vein, Verwey (2001) proposed the DPM consisting of a cognitive and motor processor. The cognitive processor is responsible for storing information pertaining to the order and organization of individual sequence elements, which have been grouped together into chunks. The motor processor contains information about the effectors' selection and activation pattern and formulates the specific effector commands to execute the desired action. Both processors are responsible for producing discrete movement sequences and drive three distinct modes of sequence execution: reaction mode, associative mode, and chunking mode (Abrahamse et al., 2013; Verwey, 2001).

In the reaction mode, responses are selected by the cognitive processor based on stimulus-response translations (Abrahamse et al., 2013). This mode is particularly employed when learning new sequences. The associative mode emerges from repeated practice in discrete sequence production tasks (DSP). In this mode, subsequent responses are influenced by preceding ones, yet they require stimulus processing for actual execution. Participants operating in the chunking mode can disregard subsequent stimuli because once motor chunks have formed, specific stimuli beyond the initial one become unnecessary. The central processor then selects these motor chunks and loads them into the motor buffer, allowing the motor processor to execute them without needing additional key-specific stimuli (Abrahamse et al., 2013).

The use of key-pressing tasks, such as the Serial Reaction Time Task (SRT) or DSP task, has become common in studies of the sequential control processes of the sequence learning of movements (Krakauer, 2019 for an overview; Nissen & Bullemer, 1987; Verwey, 1995). In the SRT task, participants initially react to a repeated visual stimulus pattern by depressing corresponding keys as quickly as possible. The subsequent stimulus emerges after a short, predetermined delay following the completion of the required action (Krakauer, 2019). Therefore, participants have to wait for each stimulus to give a response. The sequence order should adhere to a specific and fixed order, such as a sequence of 10 targets, as demonstrated by Nissen and Bullemer (1987). The response times to the visual stimuli decrease with increasing practice. Sequence knowledge is obtained by comparing the repeated and random sequences (implicit sequence learning).

In the DSP task, performers also react to visual cues displayed on the screen by depressing the corresponding keys on the keyboard. However, a major difference to the SRT is that the DSP task involves two fixed series of 3-8 stimuli presented randomly (Abrahamse et al., 2013; Krakauer, 2019). Accordingly, once participants learn the order of action required by each sequence, the initial stimulus of the respective sequence serves as a cue as to which of the two sequences should be executed. In contrast to the SRT task, participants are informed about the fixed order of the sequences, which is aimed at explicit sequence learning processes. Another difference between the two tasks is that the participant’s performance of the DSP task is evaluated after a larger number of sequence trials (between 500-1000 trials) compared to the SRT task (which has around 100 trials).

A commonality of both tasks is that these key-pressing tasks require participants to depress the corresponding keys in a fixed order (Nissen & Bullemer, 1987; Verwey, 1995). However, when visual stimuli are presented in a repetitive sequence, participants can anticipate upcoming stimuli, resulting in reduced response times even though the processes for explaining the reduction in response times differ between the two tasks (Nissen & Bullemer, 1987; Verwey, 1999).

One theoretical explanation for this phenomenon of reduced response times revolves around the process of "chunking". Thereby, several elements of the movement sequence are packaged into independent subsequences (Kovacs, Muehlbauer, et al., 2009; Sakai et al., 2003) or motor chunks (Verwey, 2001). Characteristically, the beginning of each motor chunk demonstrates a long response time for the first element and a short response time for the following elements (Muehlbauer et al., 2007; Povel & Collard, 1982). The delay to the first element of a motor chunk represents the retrieval, programming, and preparation for movement execution (Muehlbauer et al., 2007; Verwey, 2001). Therefore, the subsequent elements within the motor chunk are executed faster because the processing required for their production has already been completed (Panzer et al., 2011). The assumption is that these motor chunks are a limited number of responses, which can be selected and executed as if they were a single response (Abrahamse et al., 2013). At the beginning of practice, the transition from one motor chunk to the next one is indicated by slower response times (Abrahamse et al., 2013; Kovacs, Muehlbauer, et al., 2009). These delayed response times at the concatenation point may involve the engagement of higher cognitive processes, such as preparatory activities for the forthcoming motor chunk (Verwey, 2003).

A more seamless transition from one motor chunk to another occurs with increasing practice (Jordan, 1995; Kovacs, Muehlbauer, et al., 2009; Park & Shea, 2005). The inter-association of subsequences can be achieved through coarticulation or dynamic optimization (Jordan, 1995). Dynamic optimization links specific spatial target positions to effector movements, meaning that specific effector information is linked to sequence information. Coarticulation allows for a smoother transition between subsequences and reduces response times by facilitating the anticipation of future elements in a sequence (Jordan, 1995). A sequence response structure contains the concatenation of individual subsequences into a cohesive movement sequence (Braden et al., 2008) and the element duration, which represents the speed at which these subsequences are processed and executed (Park & Shea, 2005).

Evidence suggests that the response structure of a movement sequence is stored in a relatively abstract manner (Park & Shea, 2005; Shea et al., 2011; Wilde & Shea, 2006). This assumption is based on the results of studies in which it was indicated that a sequence with a developed response structure can be transferred to an unpracticed effector (Park & Shea, 2005), to a movement sequence rescaled in amplitude (Wilde & Shea, 2006), and into forces (Muehlbauer et al., 2007) without loss of performance, as long as the changes are proportional over the entire sequence.

While the movement organization of key-pressing tasks has been extensively investigated over the last decades (Keele et al., 1995; Nissen & Bullemer, 1987; Povel & Collard, 1982), little research has been done on more dynamic arm-movement tasks. The investigation of dynamic arm-movement tasks is important because many everyday movements require a precise regulation of muscle forces or muscle coordination of agonists and antagonists to produce the required movement (Shea et al., 2011). Therefore, in some studies sequential dynamic arm-movement tasks were used to investigate the movement sequence control (Dean et al., 2008; Kovacs, Muehlbauer, et al., 2009; Muehlbauer et al., 2007). For example, Kovacs, Muehlbauer et al. (2009) used a 14-element task, where participants had to move a limb-lever system to successively illuminated targets. The response structure was defined by the element duration (the time to move from one element to the next) and the number of zero crossings (Kovacs, Muehlbauer, et al., 2009). Zero crossings are enumerated in the acceleration trace and represent the deceleration and acceleration of the movement. Moreover, zero crossings tend to appear at the reversal points of the movement sequence, but also group near the transitions among subsequences (Park & Shea, 2005; Shea et al., 2016; Wilde & Shea, 2006). The results indicate that the movement sequence was divided into three subsequences at the start of practice, each consisting of 5 or fewer elements (Kovacs, Muehlbauer, et al., 2009). Additional practice of the element task resulted in a more seamless transition between subsequences, indicated by a decrease in zero crossings and reduced element duration time (Kovacs, Muehlbauer, et al., 2009; Park & Shea, 2005).

Due to the previous considerations, it is crucial to ascertain whether dynamic arm-movement sequences adhere to comparable principles as needed for key-pressing tasks (Shea et al., 2011). In order to expand the understanding of sequence learning, a more balanced motor and cognitive task should be incorporated that allows the transfer of theoretical concepts from key-pressing tasks to more dynamic movement sequences. Therefore, the first experiment of this dissertation involved a 16-element task. The 16-element task requires participants to move a limb-lever system, using extension/flexion movements of their elbow, in order to reach successively illuminated targets. As soon as participants hit the target, the next element lights up. The 16-element task and key-pressing task share some similarities but differ in motor demands (Shea et al., 2011). Key-pressing tasks and the 16-element task require participants to respond to a visual stimulus by pressing a key or moving the lever to a corresponding stimulus. However, the 16-element task includes the flexion and extension of the elbow joint, which requires management of movement dynamics such as, e.g., the precise control of the agonist/antagonist muscle groups and movement dynamics, such as acceleration and deceleration, at the reversal points (Shea et al., 2011).

Based on this theoretical background, the first experiment undertaken for this dissertation involved the examination of the impact of a dual-task on the stability of the response structure of a previously learned dynamic sequence task. In several studies the notion has been explored that higher cognitive processes are primarily involved in the concatenation of successive motor chunks (Abrahamse et al., 2013; Verwey et al., 2010, 2014). If this is true, a secondary task should impair the concatenation between the subsequences. Additionally, the results of recent research (Park & Shea, 2005; Shea et al., 2011) suggests that the response structure is stored abstractly and involves the determination of processing and execution speed, thereby requiring attention. Consequently, an additional secondary task should lead to increased element duration.

2.3 Sequence Learning and the Sequence Representation: The Continuous Sequence Task

Another relevant theoretical framework is the parallel neural network by Hikosaka et al. (1999), in which it is proposed that sequence learning occurs independently and in parallel in two coordinate systems. According to this perspective, one coordinate system represents the movement sequence in terms of visual-spatial coordinates (e.g., locations of the end-effector, and target locations) and the other in motor coordinates (e.g., joint angles and/or muscle activation patterns). The visual-spatial representation is fast-developing, predominantly responsible for movement execution at an early stage of practice, and requires attention, whereas the motor representation is slow-developing, guides the movement at a later stage of practice, and requires less attention (Hikosaka et al., 1999). In the parallel neural network model, it is further proposed that a dynamical shift in reliance from the visual-spatial to the motor representation occurs with increasing practice (Hikosaka et al., 1999, 2002).

Hikosaka et al. (1999, 2002) presented a model derived from their findings obtained for sequential key-pressing tasks. Bapi et al. (2000) employed a comparable experimental approach to Hikosaka et al. (1999), directing participants to execute a key-pressing sequence on a 3 x 3 grid over multiple acquisition blocks. During each trial, participants were required to press the corresponding keys on a 3 × 3 keypad while two squares were illuminated. In order to study the development of sequence representations, two transfer tests were conducted at three different practice stages (early, middle, and late practice). In these two transfer tests, the hand, or both the hand and keypad, were rotated counterclockwise by 90 degrees. Importantly, it should be noted that the same limb was consistently utilized in both of these transfer tests as during the acquisition phase. One of these tests was named ‘visual,’ involving illuminated squares appearing in the same spatial arrangement as during practice but necessitating different finger movements and a new hand position for the response. The other transfer test, labeled the 'motor' test, entailed 90-degree rotations of both the hand and the illuminated stimuli. This required the same sequence of finger movements to generate the correct response pattern. The results indicated superior motor transfer performance as the amount of practice increased compared to the visual transfer test (Bapi et al., 2000).

Based on Hikosaka et al.'s (1999) experimental approach, in recent research interesting modifications have been made to the parallel neural network model regarding the encoding and effector transfer of movement sequences (Kovacs et al., 2010; Kovacs, Han, et al., 2009; Kovacs, Muehlbauer, et al., 2009; Leinen et al., 2015). The following research employed dynamic arm-movement sequences. In previous studies it has been suggested that task characteristics, such as the number of reversals (Kovacs, Han, et al., 2009) and/or the availability of visual feedback during movement execution (Leinen et al., 2015), influence the development of a sequence representation. According to Kovacs, Han et al. (2009), a shorter sequence is mostly coded in motor coordinates, while a longer sequence is primarily coded in visual-spatial coordinates. The sequence length was determined by the number of reversals and the duration of the movement sequence. Leinen et al. (2015) have shown that removing visual information during the production of a movement sequence increased the likelihood of developing a motor representation. On the contrary, the movement sequence was more likely to be represented in visual-spatial coordinates when visual feedback was available during movement execution (also see Kovacs, et al., 2010). As a result, the authors concluded that both visual-spatial and motor codes are accessible in parallel and in a flexible manner (Leinen et al., 2015). This idea aligns with the findings of Kovacs, Muehlbauer, et al. (2009), who reported that multiple days of practice resulted in the development of multiple codes, each contributing to the production of movement sequences. These findings support Hikosaka's model that movement sequence learning allows parallel processing of sequence information.

Inspired by the parallel neural network model and the research on the determinants influencing the coding of movement sequence representation, the second experiment of this dissertation involved an examination of the attentional requirements of these two sequence representations (Hikosaka et al., 1999; 2002). Therefore, the primary objective was to investigate the attentional demands of the visual-spatial and motor representation across multiple single-task practice sessions. Another research question investigated whether the shift from visual-spatial to motor representation occurs with more single-task practice sessions. According to the theoretical background, the hypothesis involved the idea that if the visual-spatial representation is primarily responsible for sequence execution, the attentional demands will be higher compared to when the motor representation guides the movement execution.

Building upon the second experiment, the third experiment was undertaken to address the research question of how the practice conditions influence the attentional requirements of a movement sequence guided by the sequence representations (visual-spatial, motor). Although there is a growing interest in the attentional demands involved in the development of sequence representations, the question remains as to what extent dual-task or single-task practice affects the development and attentional demands of the visual-spatial and/or motor representation. Following the majority of the dual-task literature, in which it is stated that practicing two tasks simultaneously results in poor dual-task performance (Hiraga et al., 2009; Nissen & Bullemer, 1987; Schmidtke & Heuer, 1997; Schumacher & Schwarb, 2009), inferior performance was expected after dual-task practice compared to single-task practice. Another goal of this work was to examine the shift of attention at specific temporal loci during the movement sequence execution. Based on previous studies in which attentional demands were investigated during various motor tasks, it is consistently reported that these demands were higher during the beginning of the movement and decreased during movement execution (Ells, 1973; Wilke & Vaughn, 1976). Based on the findings of others that the beginning of the movement requires attention compared to the end, it was hypothesized that the beginning phase requires more attention than the middle and end (also see Wrisberg & Shea, 1978).

3 Overview of Publications

The dissertation comprises three published and peer-reviewed research articles. The complete list of publications, including those that are not part of this dissertation, can be found in the appendix.

Publication 1

Pfeifer, C., Harenz, J., Shea, C. H., & Panzer, S. (2021). Movement sequence learning: Cognitive processing demands to develop a response structure. *Journal of Cognition*, *4*(1), 1-9. https://doi.org/10.5334/joc.128

Publication 2

Pfeifer, C., Panzer, S., & Shea, C. H. (2023). Attentional demand of a movement sequence guided by visual-spatial and by motor representations. *Journal of Motor Behavior*, *55*(1), 58-67. https://doi.org/10.1080/00222895.2022.2101424

Publication 3

Pfeifer, C., Harenz, J., Shea, C. H., & Panzer, S. (2024). Dual-Task and Single-Task Practice Does Not Influence the Attentional Demands of Movement Sequence Representations. *Journal of Motor Behavior*, 1-13. https://doi.org/10.1080/00222895.2024.2327397

Experiment 1 – Movement Sequence Learning: Cognitive Processing Demands to Develop a Response Structure

Christina Pfeifer[1], Julia Harenz[1], Charles H. Shea[2] & Stefan Panzer[1+2]

[1] Saarland University, Germany

[2] Texas A&M University, United States

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http://doi.org/10.5334/joc.128

Experiment 2 – Attentional Demand of a Movement Sequence Guided by Visual-Spatial and Motor Representations

Christina Pfeifer[1], Stefan Panzer[1+2] & Charles H. Shea[2]

[1] Saarland University, Germany

[2] Texas A&M University, United States

Published in Journal of Motor Behavior (2022) 1–10

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Experiment 3 – Dual-Task or Single-Task Practice does not influence the Attentional Demands of Movement Sequence Representations

Christina Pfeifer[1], Julia Harenz[1], Charles H. Shea[2] & Stefan Panzer[1+2]

[1] Saarland University, Germany

[2] Texas A&M University, United States

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4 General Discussion

The primary objective of the work for this dissertation was to investigate the impact of a dual-task on movement sequence learning. The aim of the studies was to ascertain the impact of a dual-task on the stability of the response structure and the attentional demands of the sequence representations. The use of the dual-task methodology in motor learning research has been widespread, serving as both a tool to assess attentional demands of the primary task and as a way to explore the impact of dual-tasking on the primary task (Goh et al., 2012; 2014; Nissen & Bullemer, 1987; Verwey et al., 2014; Wrisberg & Shea, 1978). In this dissertation two variations of dynamic arm-movement tasks were presented: the 16-element task and the continuous sequence task.

Experiment 1 involved a 16-element task that was visually triggered by the illumination of the target positions. Participants had to aim with the lever at each element of the sequence as the next target element only illuminated once the preceding target element has been traversed. Due to the composition of the 16-element task of individual elements, the task was used to investigate chunking and concatenation processes. This is impossible with the continuous sequence task, as tracing a target pattern is required. The evaluated performance variables also differed between the 16-element task and the continuous sequence task used in experiments 2 and 3. The former includes the element duration, which was used to measure the time required to transition from one element to the next. In contrast, the latter includes the Root Mean Square Error, which represents the variability and the bias of the produced movement pattern from the target pattern. In addition, the continuous sequence task enables manipulation of the visual information of the target pattern during movement execution. This manipulation allowed for the examination of the pre-planning and online control processes. The participants were given a limited time of two seconds to execute the continuous sequence task and were required to trace the template as closely as possible. Both tasks were used to explore different concepts of movement sequence learning, and the findings are discussed separately. However, both tasks required controlling dynamic factors, such as regulating agonist and antagonist muscle activation, producing force, timing, accelerating, and decelerating the movement at the reversal points (Shea et al., 2016).

Three core findings were derived from the results of the three experiments. The main objective of Experiment 1 was to examine the stability of the response structure of the 16-element task to the influence of a secondary task. The results indicate that the response structure of a movement sequence task is partially vulnerable to a dual-task. The dual-task does not affect the element duration. However, the dual-task increases the processing demands related to the concatenation of subsequences, as represented by an increase in zero crossings.

One goal of Experiment 2 was to determine the attentional requirements of sequence representations following single-task practice over multiple days. The results show that both sequence representations require attention after one and two days of single-task practice of the continuous sequence task. However, during the early stages of learning, the motor representation was found to guide movement execution in a dual-task situation, while the visual-spatial representation is particularly vulnerable to the probe task. After two days of single–task practice, both sequence representations were found to guide the movement execution. Furthermore, an additional day of single-task practice did not reduce the attentional demands of either sequence representation.

Experiment 3 involved an investigation of the influence of dual-task and single-task practice on the shift of attentional demands of sequence representations. The results of the study indicate that the beginning of the movement is more attentionally demanding than the end of the movement, regardless of the practice condition. Additionally, neither dual-task nor single-task practice impacted the shift of attentional demands of the two sequence representations.

The results are discussed and embedded in the respective theoretical frameworks in the following chapter. In Chapter 4.1 the chunking and concatenation processes of the DSP task and the 16-element task are delineated. The impact of a secondary task on both tasks is further discussed. In Chapter 4.2 the findings of experiments 2 and 3 are highlighted, along with their relation to Hikosaka et al.'s (1999) parallel neural network model and the development of the sequence representations. Subsequently, the attentional demands of the sequence representation as one characteristic of the parallel neural network model are discussed.

4.1 The Impact of Dual-Tasking on the Response Structure

When movement sequences are performed for the first time, they are typically executed slowly, jerkily, and discretely (Ramkumar et al., 2016; Muehlbauer et al., 2007). However, with increasing practice, the time required to transition from one element to the next decreases, and the concatenation of the independent subsequences moves towards being seamless (Park & Shea, 2005; Wilde & Shea, 2006). These processes represent aspects of the development of a response structure. In particular, the response structure includes the linkages between individual subsequences (Braden et al., 2008) and the processing and execution speed of the subsequences (Park & Shea, 2005). Park and Shea (2005) have suggested that a developed sequence response structure is stored abstractly. In this context, it is proposed based on sequence learning models that an abstractly stored representation is attentionally demanding (Hikosaka et al., 2002).

Previous studies using the multiple-element task were conducted to examine whether more dynamic arm-movement sequences are organized and learned in a similar manner to discrete key-pressing sequences (Kovacs, Muehlbauer, et al., 2009; Park & Shea, 2005). The multiple-element task provides a performance measurement similar to that of key-pressing tasks (response time/ element duration) as well as continuous measures of performance such as kinematic data (e.g., acceleration, velocity, displacement). This supplies some insights into the learning, structuring, and producing of more dynamic arm-movement sequences. Consequently, the dynamic arm-movement task encompasses a more balanced combination of cognitive and motor processes involved in sequence control (Shea et al., 2011). The cognitive process involves the organization and chunking together of the elements of the movement sequence, whereas the motor process involves the selection of specific effectors, precise control of agonist and antagonist muscle groups, and the control of movement dynamics to regulate forces during, e.g., acceleration and deceleration at the reversal points (Shea et al., 2016; Verwey et al., 2010).

Both chunking and concatenation processes are observed and studied in multiple element tasks as well as in key-pressing tasks such as the DSP task (Abrahamse et al., 2013; Braden et al., 2008; Park & Shea, 2005). These processes are derived from the relevant response times for the DSP task and the 16-element task; moreover, they are also reflected in the number of zero crossings for the 16-element task. Both tasks generate subsequences comprising multiple elements or key-presses with the response time to the first element of a subsequence being extended compared to all other elements or key-presses in the subsequence (Braden et al., 2008; Kovacs et al., 2009; Park & Shea, 2005; Verwey, 2003). This delay reflects the concatenation of the subsequences/ motor chunks (Abrahamse et al., 2013; Park & Shea, 2005; Verwey, 2001). However, one method which can be used to identify the segmentation of the subsequence in the DSP task is based on comparisons of response times (Abrahamse et al., 2013; Verwey et al., 2010). For this the response times of the respective key-presses are analyzed in comparison to the initial key-press response time of the sequence (Abrahamse et al., 2013; Verwey et al., 2010). This method assumes that chunking remains unchanged with practice, leading to reduced sensitivity to detect chunking structures during practice (Abrahamse et al., 2013). In this regard, the 16-element task offers an advantage as it facilitates discrete and continuous performance measures. In a study by Park and Shea (2005) it was found that a movement sequence task consisting of 16 elements was divided into five subsequences at the beginning and three subsequences at the end of the practice. However, the segmentation of the movement sequence may vary throughout practice. The analysis of zero crossings can be viewed as an extension of the element duration method, which is used to identify the concatenation points of a movement sequence. This is because zero crossings are recorded at the reversal points of a movement sequence and at the points in time where the slowest element durations of the movement sequence are detected, marking the transition between subsequences (Park & Shea, 2005). The main finding of Experiment 1 is that only the concatenation of subsequences and not the element duration of executing subsequences is vulnerable to the secondary task. The number of zero crossings substantially increased under dual-task compared to single-task conditions. This result is in agreement with the notion that concatenation involves parallel processing such as loading and initiation of the following subsequence during the execution of the current subsequence (Abrahamse et al., 2013; Panzer & Shea, 2008; Verwey, 2003). Therefore, retrieving and preparing the subsequent motor chunk involves processing demands (Park & Shea, 2008; Verwey, 2001). The secondary task caused additional processing demands reflected by an increased number of zero crossings. However, it is essential to note that the additional zero crossings were observed between the reversal points, near the presentation of the secondary task and the required motor response. These additional zero crossings may indicate structural interference, as both the primary task and the secondary task require the same response modality (Wickens, 1984).

Verwey et al. (2010) examined the impact of a secondary task, a tone-counting task, on the DSP task. The results revealed that the undertaking of the secondary task resulted in an overall longer response time for the sequence. This increase did not significantly differ at the concatenation points of the subsequences, or any other time point during movement execution (Verwey et al., 2010). Moreover, the response time of the DSP task was found to be comparable to the element duration of the 16-element task. The results obtained in the work of this dissertation did not reveal an increase in the element duration when a secondary task was presented. It was found that once the subsequence is executed, a secondary task no longer affects the execution and processing speed of a response structure. However, it is worth noting that in the secondary task of Verwey et al. (2010), participants were required to perform a tone-counting task that continuously placed demands on their working memory. This continuous secondary task induced constant interference with the primary task, which may have led to the elevated overall response times observed in Verwey's work. In contrast to this, Experiment 1 involved a discrete auditory secondary task for the analysis of the processing demands at two specific time points during movement execution. The time points for the secondary task were introduced for elements 7 and 12 of the sequence in which the acceleration and deceleration were balanced to prevent additional processing demands related to response execution (Fitts, 1954; Shea et al., 2019).

In general, the response structure of a movement sequence characterized by numerous elements is believed to mitigate the extent of processing and cognitive intervention in control processes (Abrahamse et al., 2013; Shea et al., 2011). However, cognitive processing is still necessary (Shea et al., 2011). The results obtained in Experiment 1 support this assumption and suggest that the response structure is somewhat resistant to a discrete secondary task. The element duration represents the processing and execution speed, which was unaffected by the secondary task. Therefore, imposing a response structure in order to control processing and execution speed reduced the processing demands. According to the DPM introduced in Verwey (2001), this means that when the chunking mode directs execution, the motor processor executes the chunks without requiring additional processing demands. However, based on the increased number of zero crossings in the dual-task situation, it appears that the concatenation of the individual chunks still requires processing and attention. Therefore, the secondary task induced further processing demands that exceeded the capacity available for concatenating the chunks. Future research should concentrate on determining the impact of prolonged practice on the concatenation process. The results of a study by Kovacs, Muehlbauer, et al. (2009) indicate that the element duration of the initial element in the subsequences decreased with practice. Extended practice may result in the refinement of the response structure, with subsequent inter-association of the elements in the subsequences due to co-articulation or dynamic optimization (Jordan, 1995). However, it needs to be investigated whether additional practice strengthens the concatenation between subsequences of a dynamic arm-movement task and induces fewer performance impairments through a secondary task.

4.2 The Impact of Dual-Tasking on the Sequence Representations

According to Hikosaka et al. (1999), movement sequence learning occurs independently and in parallel in two coordinate systems. This perspective posits that one represents the movement in visual-spatial coordinates (e.g., target location or/and spatial location of the effector) and the other in motor coordinates (e.g., joint angles and/and muscle activation patterns). The visual-spatial representation is primarily responsible for movement execution at an early stage of learning and requires attention. However, the motor representation guides the movement execution at a later stage of learning and requires less attention (Hikosaka et al., 1999).

The results of experiments 2 and 3 demonstrate that, after one day of practice (single-task or dual-task practice), the motor representation guides the sequence execution in a dual-task situation. This finding is only partially consistent with the model used in Hikosaka (1999), where it is argued that the visual-spatial representation is predominantly responsible for sequence execution at an early stage of learning, while the motor representation guides the movement sequence at a later stage of learning. The results of recent studies have provided empirical evidence that the following factors such as the movement sequence length (Kovacs, Han, et al., 2009) and the availability of concurrent visual feedback during movement sequence execution influence the development of sequence representations (Kovacs, Muehlbauer, et al., 2009; Leinen et al., 2015; Panzer et al., 2009, 2024; Shea et al., 2011). In an earlier study by Leinen et al. (2015) the influence of concurrent visual feedback on sequence representation development was investigated. Participants acquired a movement sequence similar to the continuous sequence task with or without concurrent visual feedback. The concurrent visual feedback was altered during the transfer tests. Participants who did not receive concurrent visual feedback during the acquisition phase were given concurrent visual feedback during the transfer tests. In contrast, those who had concurrent visual feedback during the acquisition phase did not receive any during the transfer tests. When concurrent visual feedback was available during movement sequence production, feedback-based adjustments of an ongoing movement were possible, and the movement was primarily represented in visual-spatial coordinates (Leinen et al., 2015). These adjustments were not observed when the concurrent visual information was withheld during sequence execution. Therefore, withholding visual feedback increased the likelihood of representing the movement sequence in motor coordinates (Leinen et al., 2015). The results obtained in experiments 2 and 3 demonstrate the development of a dominant motor representation, particularly at the early stages of learning and in the dual-task situation when concurrent visual feedback is absent.

The results of Experiment 2 suggest that after two days of practice, both representations guide the movement sequence in a dual-task situation. This finding challenges the assumptions made by Hikosaka et al. (1999) and the experimental data from Bapi et al. (2000) that the reliance shifts from visual-spatial to motor with increasing practice. One possible interpretation for the present finding could be that participants had to retrieve the spatial locations of the target pattern from working memory during the execution of the sequence. Retrieving target information from memory may have delayed the development of an effective visual-spatial or motor representation. Additionally, the probe task may have prolonged this process. A more moderate view of the Hikosaka model, highlighting the parallel development of both sequence representations, suggests that both are available and utilized for sequence production (Hikosaka et al., 1999). Accordingly, both sequence representations contribute to movement production after two days of single-task practice. This notion is supported by the experiment of Kovacs, Muehlbauer et al. (2009) that involved practicing a 14-element sequence of elbow extension-flexion movements for 1, 4, and 12 days. Regardless of the number of practice sessions, the results showed better transfer performance when the visual coordinates, which included the visual display of the targets, and the same spatial positions were reinstated during the transfer test compared to when the motor coordinates were reinstated. However, mirror transfer performance improved when the concurrent vision of the target positions of the movement sequence was obscured. This result illustrates that multiple codes, visual-spatial, and motor, are developed during practice. Each code contributes to sequence performance when the respective coordinates are responsible for response production instead of a single dominant code (Kovacs, Muehlbauer et al., 2009). However, it is essential to consider that the early and late stages of learning are not ascribed to precise time frames in the model of Hikosaka (1999). Even when Hikosaka states 'stages of learning,' the results obtained in the work for this dissertation indicate that the shift of the dominantly guiding sequence representation may occur gradually (Zirngibl & Koch, 2002). Possibly it is the case, that two days of practice may not be sufficient to develop an effective visual-spatial or motor representation for sequence production without concurrent visual information about the target and limb position.

The main research focus of experiments 2 and 3 was to investigate the attentional demands of the sequence representations as another characteristic of the parallel neural network model. According to Hikosaka et al. (1999), the visual-spatial representation requires more attention than the motor representation when guiding the sequence production. Based on the assumptions of the probe paradigm and regarding the capacity limits of the human information processing system (Goh et al., 2014; Heuer, 1996), it is essential to compare the performance of the probe task in both dual-task and single-task situations. Such a comparison will enable an assessment of the attentional demands of the two sequence representations.

Experiment 2 involved the investigation of the overall attentional demands of the visual-spatial and the motor sequence representation. The findings obtained indicate that both the visual-spatial and the motor sequence representations require attention for sequence execution. The results of Experiment 2 are not consistent with the assumption proposed by Hikosaka et al. (1999, 2002). However, a more moderate interpretation of the Hikosaka model does not suggest that the motor representation requires no attention at all, but somewhat less attention than the visual-spatial representation (Hikosaka et al., 1999, 2002). Following on from the results of Experiment 2, an additional research question emerged concerning which specific time points (beginning, middle, end) during movement execution guided by the sequence representations are attention-demanding. The probe paradigm facilitates the investigation of attentional demands at different temporal loci of a movement, such as the beginning, middle, and end (Ells, 1973; Wilke & Vaughn, 1976). Consistent with the existing literature, the results obtained in the work for this dissertation indicate that the beginning of the movement is more attention-demanding compared to the end (Ells, 1973; Kerr, 1975; Wilke & Vaughn, 1976). Thus, the findings indicate that premovement processes such as decision-making and preprogramming occupy processing capacities during movement initiation. This approach is also consistent with Glover's planning-control model (2004), in which it is proposed that there is a distinction between the planning and control phase of action (see also Woodworth, 1899). The planning system selects the initial kinematics of a movement, such as velocity and timing, before movement execution, while the control system gradually takes over and minimizes spatial errors in the movement (Glover, 2004). It could be postulated that selecting an appropriate motor program for movement execution necessitates high attentional demands. Furthermore, it is reasonable to suggest that the lack of concurrent visual information caused the control system to use proprioceptive feedback and the efference copy of the planning system to reduce spatial errors (Glover, 2004).

Experiments 2 and 3 involved the examination of the influence of different practice conditions on the attention demands of the movement sequence representation. The practice conditions included one day and two days of single-task practice, as well as single-task and dual-task practice. The results of the experiments indicated that the practice conditions did not influence the attentional demands of the sequence representations in the response production of the continuous sequence task. Both representations require attention when guiding the sequence execution regardless of the respective practice conditions. However, in Experiment 2, the practice condition impacted the transfer performance of the continuous sequence task. Specifically, the visual-spatial representation demonstrated vulnerability to the secondary task after just one day of single-task practice. This was no longer observable after two days of practice.

In Experiment 3 the attention demands of the sequence representations were compared after dual-task or single-task practice. At present, there is no consensus in the dual-tasking literature on whether dual-task practice leads to improved or worsened performance (see Strobach, 2020 for a review). Therefore, in various studies different practice methods have been utilized when investigating capacity demands during movement learning, such as examining the capacity demands during skill acquisition (Eversheim & Bock, 2001) or the impact of extensive practice on dual-tasking (Strobach, 2020; Strobach et al., 2014). On the one hand, in certain studies a decline has been documented in performance when learning movement sequences in a dual-task situation (Hiraga et al., 2008; Nissen & Bullemer, 1987; Schumacher & Schwarb, 2009), and on the other hand others observed improvements (Goh et al., 2012; Hemond et al., 2010). In contrast to the results obtained in Experiment 3, previous studies have reported there to be a benefit from practicing two tasks simultaneously, particularly in regard to reducing dual-task interferences (Goh et al., 2012; Schmidtke & Heuer, 1997). This reduction can be attributed to task integration (Koch et al., 2018; Schmidtke & Heuer, 1997; Strobach, 2020). Thus, two initially separate tasks are intertwined after practice in such a way that they can be performed together (Koch et al., 2018). Strobach et al., (2020) have assumed that two tasks with separate capacity-limited processes are integrated into a "super task" with merged capacity-limited processes. Dual-task practice is necessary for task integration, as opposed to just practicing particular tasks in single-task sessions (Koch et al., 2018). However, the dual-task practice advantage concerning task integration may vary based on the specific dual-task combinations (Strobach et al., 2020). For instance, the execution of cued association tasks that require accessing long-term memory activates mechanisms that facilitate the integration of these two tasks. The combination of a continuous tracking task with a sensorimotor or cognitive task, however, failed to achieve the same outcome (Strobach et al., 2020). In another study, Panzer et al. (2024) tested the idea of across-task binding between a continuous sequence task and a tone discrimination task. Across-task binding refers to the process of linking the stimulus of one task to the stimulus or response of another task (Panzer et al., 2024). After one day of dual-task practice, participants did not bind either visual-spatial or motor information to the auditory information of the discrimination task. The authors concluded that sequence information and auditory information are processed in two independent modules even though the tone discrimination task was predictable and occurred at the same time points during movement execution (Keele et al., 2003; Panzer et al., 2024). Existing research has not found evidence of either across-task binding or task integration between a continuous sequence task and an auditory secondary task. It is important to note that the task integration hypothesis and across-task binding are linked to theoretically different concepts. The former involves the assumption of an integration of two capacity-limiting processes into one, which is based on the central capacity theory, while the latter is not necessarily based on the central capacity theory but necessitates an examination of associations/ linkages/ correlations between tasks from different modalities. Despite is being suggested in some studies (see Strobach, 2020 for a review), it is unclear whether additional practice sessions would have decreased attentional demands in experiment 2 and 3. However, reducing attentional demands was not the primary focus of these experiments.

5 Conclusion and Outlook

Modern life often requires dual-tasking, such as speaking to an assistant driver while driving a car or typing a message on the computer while a colleague interrupts with an urgent matter that requires a quick response. Additionally, certain professions, such as teachers, pilots, air traffic controllers, surgeons, and athletes, require dual-tasking in their work situations. In certain circumstances, carrying out one task while simultaneously performing another may be feasible, such as driving a car and engaging in conversation. However, in other situations, it can be difficult to perform multiple tasks simultaneously, such as typing and speaking. The presented experiments offer some insights into the impact of a dual-task on sequence learning. This sheds light on the stability of a response structure and the attentional demands of sequence representations. The implications of these findings are relevant for both theoretical and practical applications.

From a theoretical perspective, the results of all experiments indicated that a discrete auditory secondary task affected movement sequence learning. The 16-element and continuous sequence tasks were susceptible to an auditory secondary task. Certainly, it is crucial to consider the different influences on the respective sequence tasks since both differ in the sequence learning processes that need to be investigated.

The main findings of Experiment 1 indicate that the concatenation of subsequences is particularly vulnerable to dual-tasking. This suggests that a dual-task incurs additional processing demands at the concatenation points of a movement sequence, which is in agreement with the notion of parallel processing (Brown & Carr, 1989; Kovacs, Muehlbauer, et al., 2009). In the context of parallel processing, the next subsequence is prepared during the execution of the current subsequence, which requires processing capacity (Kovacs, Muehlbauer, et al., 2009). However, as soon as the subsequence is executed, a dual-task does not influence the processing and execution speed. Therefore, information capacity is increased by organizing input and output units into structured chunks (Miller, 1956). This finding is also noteworthy for its practical application, as everyday movements, especially sports-related movements, comprise multiple subsequences. The chunking and the concatenation of subsequences is a constant process in daily life. For instance, this occurs when we are typing, playing the piano, or dialing a phone number. Known telephone numbers, for example, are often organized in several groups of 2 to 4 numbers. As an illustration, the number sequence 015737838223 could be divided into four possible subsequences: 0157 – 378 – 382 - 23. The presence of an additional discrete secondary task when dialing the phone number may increase processing costs for the concatenation from one subsequence to the next, presumably resulting in the formation of smaller subsequences when dialing the telephone number or even creating momentary lapses. Since sports movements such as dancing, gymnastics, and figure skating also consist of long sequences of movements, it is worth investigating whether principles such as chunking or the concatenation of these subsequences, which are mainly derived from laboratory tasks, can be transferred to gross motor movements where more degrees of freedom have to be controlled (Wulf & Shea, 2002). Additionally, it could be worth investigating whether a dual-task would have a similar effect on these gross motor tasks compared to the laboratory tasks.

The results of experiments 2 and 3 demonstrate that the continuous sequence task was susceptible to a secondary task. Specifically, during the early stages of learning, the movement sequence represented in visual-spatial coordinates was initially vulnerable to an auditory secondary task. Thus, during the early stages of learning, when a dual-task occurred, the movement sequence was primarily represented in motor codes. However, increasing practice strengthens visual-spatial and motor representations, so both are responsible for movement execution. Overall, the present results support a more moderate view of the parallel neural network model by Hikosaka et al. (1999), as already suggested by numerous studies (Kovacs, Han, et al., 2009; Kovacs, Muehlbauer, et al., 2009; Leinen et al., 2015; Panzer et al., 2009; Shea et al., 2011). In previous studies it has been found that both representations develop in parallel and are accessible from the beginning of a learning process (Kovacs, Muehlbauer, et al., 2009; Leinen et al., 2015). This evidence supports the multiple coding notion, which posits that each code (visual-spatial, motor) contributes to the sequence performance. Although Hikosaka's model involves consideration of a parallel development of the representations, there is also an assumed shift in reliance from the visual-spatial representation to the motor representation with increasing practice. However, the results of recent work, such as obtained by Kovacs, Muehlbauer, et al. (2009), did not show a shift in reliance on the respective sequence representations of a continuous sequence task and increasing practice sessions even up to 12 days. Instead, factors such as concurrent visual feedback and sequence length were found to determine which representation dominates of a dynamic arm-movement task (Kovacs, Muehlbauer, et al., 2009; Leinen et al., 2015; Panzer et al., 2024). The sequence representations for a key-pressing task, such as the *m x n* task, may be developed in a few practice trials. Consequently, a shift of these sequence representations may be observed earlier (Bapi et al., 2000; Wulf & Shea, 2002).

The presented experiments of the work for this dissertation were the first in which the attentional demands of sequence representations of a continuous sequence task were investigated. The probe task was consistently presented at one of the reversal points precisely when a movement from extension to flexion was required. Introducing a probe task at the reversal point had a detrimental effect on secondary task performance because the additional demands competed with limited processing capacities (Kahneman, 1973; Wulf & Shea, 2002). The information processing model indicates that the deceleration and re-acceleration of the movement impose additional processing demands on response execution (Fitts, 1954; Shea et al., 2019). Consequently, future research should consider introducing the probe task at the point of movement where constant acceleration is required (between the reversal points), and fewer processing requirements can be assumed. This approach could further differentiate the attention demands required during movement execution, allowing for a more accurate derivation and/or prediction of expected dual-task interferences.

The Hikosaka model (1999) may have practical implications because everyday movements, such as driving a car, are represented in visual-spatial and motor coordinates. For example, visual-spatial coordinates could refer to the road or the location of the gear stick, while motor coordinates refer to muscle activation patterns and required joint angles to steer the wheel. Disentangling the sequence representations of gross motor movements to determine which is action-guiding in everyday life is a challenging aspect of research. According to the presented results in this dissertation, both representations require attention for movement execution. When performing a continuous task in a natural environment, such as driving along a winding road with frequent direction changes, like hairpin bends, a secondary task could cause interference. Therefore, turning down the radio or pausing conversations with the assistant driver on such routes is common practice to preserve attentional capacity, as often reported anecdotally. The present theoretical concepts can be investigated effectively in laboratories with highly scaled and fine-graded variables. Nevertheless, advancing dual-task research in more natural real-world tasks would also be interesting, where such fine-grained analysis may not necessarily have practical significance.

It has been suggested in the literature, that additional aspects of the dual-task determine the success or failure of two tasks. However, it is essential to mention that in this dissertation these additional factors that could improve dual-task performance were not explored, such as input and output modality compatibility (Hazeltine et al., 2006; Koch et al., 2018; Ruthruff et al., 2006) or extended (dual-task) practice (Cuppone et al., 2018; Eversheim & Bock, 2001; Shah et al., 2023). However, these aspects play a crucial role in the extent of dual-task interference and have been researched for several years. The modality compatibility of the two tasks affects the extent of dual-task interference. While dual-task performance can be increased through the combination of visual-manual and auditory-vocal tasks, these effects were diminished when various modality pairings, such as visual-vocal tasks coupled with auditory-manual tasks, were employed in the studies (Hazeltine et al., 2006; Ruthruff et al., 2006). It is plausible that modality-specific factors may contribute to dual-task interference that cannot be mitigated entirely through practice (Schumacher & Schwarb, 2009; Van Selst et al., 1999). Consequently, it is crucial to recognize that there are limitations to practice-based demonstrations of plasticity (Koch et al., 2018).

In this context, two points may be subject to criticism since both tasks in the experiments undertaken for this dissertation necessitated a motor response. This could have resulted in structural inferences that increased practice cannot attenuate. Additionally, the modality compatibility of the secondary task may also be a point of contention, as the auditory stimulus required a motor response. Optimal practice effects seem attainable only when employing so-called 'standard' stimulus-response approaches, as Hazeltine et al. (2006) proposed, which involve a natural inclination to associate visual stimuli with manual responses and auditory stimuli with vocal responses. It would be intriguing in future research to alter the motor response of the secondary auditory task to a verbal response and subsequently investigate the respective dual-task interferences and attention demands of the sequence representations.

According to recent studies, extensive practice can significantly decrease dual-task interference by reducing the demands of the primary task (Cuppone et al., 2018; Eversheim & Bock, 2001; Shah et al., 2023). However, the nature of the motor task and the experimental manipulations must be considered to elicit possible comparisons across multiple studies. For instance, Shah et al. (2023) examined the effects of extended single-task practice on the accuracy and temporal efficiency of a reaching task. By applying the dual-task methodology, Shah et al. (2023) reported that ten hours of training indicated a resistance to dual-task interferences. In another study task integration of an auditory and visual task has been demonstrated after 90 dual-task practice trials (Schmidtke & Heuer, 1997). The variety of results and experimental procedures make finding the appropriate number of practice trials or days challenging. However, it can be argued that when there is no difference between single- and dual-task performance this could indicate ‘sufficient’ practice (Goh et al., 2014). Therefore, future studies could focus on increasing the number of dual-task practice sessions to investigate the reduction of dual-task interferences between a continuous sequence task and a probe task.

References

Abrahamse, E. L., Ruitenberg, M. F., De Kleine, E., & Verwey, W. B. (2013). Control of automated behavior: insights from the discrete sequence production task. *Frontiers in Human Neuroscience*, *7*, 82.

Allport, D. A., Antonis, B., & Reynolds, P. (1972). On the division of attention: a disproof of the single channel hypothesis. *The Quarterly Journal of Experimental Psychology*, *24*(2), 225–235. https://doi.org/10.1080/00335557243000102

Bapi, R. S., Doya, K., & Harner, A. M. (2000). Evidence for effector independent and dependent representations and their differential time course of acquisition during motor sequence learning. *Current Opinion in Psychiatry*, *13*(3), 271–273.

Bayot, M., Dujardin, K., Tard, C., Defebvre, L., Bonnet, C. T., Allart, E., & Delval, A. (2018). The interaction between cognition and motor control: A theoretical framework for dual-task interference effects on posture, gait initiation, gait and turning. N*europhysiologie Clinique*, *48*(6), 361-375.

Boutin, A., Fries, U., Panzer, S., Shea, C. H., & Blandin, Y. (2010). Role of action observation and action in sequence learning and coding. *Acta Psychologica*, *135*(2), 240–251. https://doi.org/10.1016/j.actpsy.2010.07.005

Braden, H. W., Panzer, S., & Shea, C. H. (2008). The effects of sequence difficulty and practice on proportional and nonproportional transfer. *Quarterly Journal of Experimental Psychology*, *61*(9), 1321–1339. https://doi.org/10.1080/17470210701557639

Broadbent, D.E. (1958). *Perception and communication.* Pergamon Press.

Brown, T. L., & Carr, T. H. (1989). Automaticity in skill acquisition: Mechanisms for reducing interference in concurrent performance. *Journal of Experimental Psychology: Human Perception and Performance*, *15*(4), 686.

Clegg, B. A., DiGirolamo, G. J., & Keele, S. W. (1998). Sequence learning. *Trends in Cognitive Sciences*, *2*(8), 275–281. https://doi.org/10.4324/9781315791227-4

Cuppone A.V., Semprini M., Konczak J. (2018). Consolidation of human somatosensory memory during motor learning. *Behavioural Brain* Research,347. 184-192. https://doi.org/10.1016/j.bbr.2018.03.013

Dean, N. J., Kovacs, A. J., & Shea, C. H. (2008). Transfer of movement sequences: Bigger is better. *Acta Psychologica*, *127*(2), 355–368. https://doi.org/10.1016/j.actpsy.2007.07.004

Deutsch, J.A., & Deutsch, D. (1963). Attention: Some theoretical considerations. *Psychological Review, 70,* 80-90.

Ells, J. G. (1973). Analysis of temporal and attentional aspects of movement control. *Journal of Experimental Psychology*, *99*(1), 10–21. https://doi.org/10.1037/h0034740

Esmaeili Bijarsari, S. (2021). A current view on dual-task paradigms and their limitations to capture cognitive load. *Frontiers in Psychology*, *12*, 648586. https://doi.org/10.3389/fpsyg.2021.648586

Eversheim, U., & Bock, O. (2001). Evidence for processing stages in skill acquisition: A dual-task study. *Learning and Memory*, *8*(4), 183–189. https://doi.org/10.1101/lm.39301

Fitts, P. (1954). Information capacity of discrete motor responses. *Journal of Experimental Psychology*, *47*(6), 381–391.

Glover, S. (2004). Separate visual representations in the planning and control of action. *Behavioral and Brain Sciences*, *27*(01), 3–78. https://doi.org/10.1017/s0140525x04000020

Goh, H. T., Gordon, J., Sullivan, K. J., & Winstein, C. J. (2014). Evaluation of attentional demands during motor learning: Validity of a dual-task probe paradigm. *Journal of Motor Behavior*, *46*(2), 95–105. https://doi.org/10.1080/00222895.2013.868337

Goh, H. T., Sullivan, K. J., Gordon, J., Wulf, G., & Winstein, C. J. (2012). Dual-task practice enhances motor learning: A preliminary investigation. *Experimental Brain Research*, *222*(3), 201–210. https://doi.org/10.1007/s00221-012-3206-5

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

Hemond, C., Brown, R. M., & Robertson, E. M. (2010). A distraction can impair or enhance motor performance. *Journal of Neuroscience*, *30*(2), 650–654. https://doi.org/10.1523/JNEUROSCI.4592-09.2010

Heuer, H. (1996). Dual-task performance. In Neumann, O. & Sanders, A.F., *Handbook of Perception and Action* (Vol. 3, 113-153). Academic Press. https://doi.org/10.1016/S1874-5822(96)80021-1

Hikosaka, O., Nakahara, H., Rand, M. K., Sakai, K., Lu, X., Nakamura, K., Miyachi, S., & Doya, K. (1999). Parallel neural networks for learning sequential procedures.

Trends in Neurosciences, *22*(10), 464–471. https://doi.org/10.1016/S0166-2236(99)01439-3

Hikosaka, O., Nakamura, K., Sakai, K., & Nakahara, H. (2002). Central mechanisms of motor skill learning. *Current Opinion in Neurobiology*, *12*(2), 217–222. https://doi.org/10.1016/S0959-4388(02)00307-0

Hiraga, C. Y., Garry, M. I., Carson, R. G., & Summers, J. J. (2009). Dual-task interference: Attentional and neurophysiological influences. *Behavioural Brain Research*, *205*, 10–18. https://doi.org/10.1016/j.bbr.2009.07.019

Jordan, M. I. (1995). The organization of action sequences: Evidence from a relearning task. *Journal of Motor Behavior*, *27*(2), 179–192. https://doi.org/10.1080/00222895.1995.9941709

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

Keele, S. W., Ivry, R., Mayr, U., Hazeltine, E., & Heuer, H. (2003). The Cognitive and Neural Architecture of Sequence Representation. *Psychological Review*, *110*(2), 316–339. https://doi.org/10.1037/0033-295X.110.2.316

Keele, S. W., Jennings, P., Jones, S., Caulton, D., & Cohen, A. (1995). On the modularity of sequence representation. *Journal of Motor Behavior*, *27*(1), 17–30. https://doi.org/10.1080/00222895.1995.9941696

Kerr, B. (1975). Processing demands during movement. *Journal of Motor Behavior*, *7*(1), 15–27. https://doi.org/10.1080/00222895.1975.10735009

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

Kovacs, A. J., Boyle, J., Grutmatcher, N., & Shea, C. H. (2010). Coding of on-line and pre-planned movement sequences. *Acta Psychologica*, *133*(2), 119–126. https://doi.org/10.1016/j.actpsy.2009.10.007

Kovacs, A. J., Han, D. W., & Shea, C. H. (2009). Representation of movement sequences is related to task characteristics. *Acta Psychologica*, *132*(1), 54–61. https://doi.org/10.1016/j.actpsy.2009.06.007

Kovacs, A. J., Muehlbauer, T., & Shea, C. H. (2009). The Coding and Effector Transfer of Movement Sequences. *Journal of Experimental Psychology: Human Perception and Performance*, *35*(2), 390–407. https://doi.org/10.1037/a0012733

Krakauer, J. W., Hadjiosif, A. M., Xu, J., Wong, A. L., & Haith, A. M. (2019). Motor learning. *Comprehensive Physiology*, *9*(2), 613–663. https://doi.org/10.1002/cphy.c170043

Lashley, K.S. (1951). The problem of serial order in behavior. In L.A. Jeffress, *Cerebral Mechanisms in Behavior* (pp. 112-136). Wiley.

Leinen, P., Shea, C. H., & Panzer, S. (2015). The impact of concurrent visual feedback on coding of on-line and pre-planned movement sequences. *Acta Psychologica*, *155*, 92–100. https://doi.org/10.1016/j.actpsy.2014.12.005

Magill, R., & Anderson, D. I. (2017). *Motor learning and control.* McGraw-Hill Publishing.

Massing, M., Blandin, Y., & Panzer, S. (2018). The influence of eye-movements on the development of a movement sequence representation during observational and physical practice. *Acta Psychologica*, *182*, 1–8. https://doi.org/10.1016/j.actpsy.2017.10.008

Miller G.A. (1956). The magical number seven, plus or minus two: some limits on our capacity for processing information. *The Psychological Review* 63(2): 81–97.

Muehlbauer, T., Panzer, S., & Shea, C. H. (2007). The transfer of movement sequences: Effects of decreased and increased load. *Quarterly Journal of Experimental Psychology*, *60*(6), 770–778. https://doi.org/10.1080/17470210701210957

Navon, D., & Gopher, D. (1979). On the economy of the human-processing system. *Psychological Review,* 86, 214–255. http://dx.doi.org/10.1037/0033-295X.86.3.214

Neumann, O. (1992). Theorien der Aufmerksamkeit: von Metaphern zu Mechanismen. *Psychologische Rundschau*, *43*, 83-101.

Neumann, O. (1996). Theories of attention. In Neumann, O. & Sanders, A.F., *Handbook of perception and action* (Vol. 3, pp. 389-446). Academic Press.

Nissen, M. J., & Bullemer, P. (1987). Attention Requirements of Learning Evidence from Performance Measures. *Cognitive Psychology*, *19*, 1–32. https://doi.org/10.1016/0010-0285(87)90002-8

Panzer, S., Gruetzmacher, N., Fries, U., Krueger, M., & Shea, C. H. (2011). Age-related effects in interlimb practice on coding complex movement sequences. *Human movement science*, *30*(3), 459-474.

Panzer, S., Pfeifer, C., Daniel, L., Gaschler, R., Haider, H., & Shea, C. H. (2024). Across-task binding: The development of a representation in learning a continuous movement sequence. *Human Movement Science*, *94*, 103195. https://doi.org/10.1016/j.humov.2024.103195

Panzer, S., & Shea, C. H. (2008). The learning of two similar complex movement sequences: Does practice insulate a sequence from interference? *Human Movement Science*, *27*(6), 873–887. https://doi.org/10.1016/j.humov.2008.02.021

Park, J. H., & Shea, C. H. (2005). Sequence learning: Response structure and effector transfer. *Quarterly Journal of Experimental Psychology Section A: Human Experimental Psychology*, *58*(3), 387–419. https://doi.org/10.1080/02724980343000918

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

Poljac, E., Kiesel, A., Koch, I., & Müller, H. (2018). New perspectives on human multitasking. *Psychological Research*, *82*(1), 1–3. https://doi.org/10.1007/s00426-018-0970-2

Povel, D. J., & Collard, R. (1982). Structural factors in patterned finger tapping. *Acta Psychologica*, *52*(1–2), 107–123. https://doi.org/10.1016/0001-6918(82)90029-4

Ramkumar, P., Acuna, D. E., Berniker, M., Grafton, S. T., Turner, R. S., & Kording, K. P. (2016). Chunking as the result of an efficiency computation trade-off. Nature communications, 7(1), 1–11. https://doi.org/10.1038/ncomms12176

Rosenbaum, D.A., Kenny, S., & Derr, M.A. (1983). Hierarchical control of rapid movement sequences. *Journal of Experimental Psychology: Human Perception and Performance, 9*, 86-102.

Ruthruff, E., Hazeltine, E., & Remington, R. W. (2006). What causes residual dual-task interference after practice? *Psychological Research*, *70*(6), 494–503. https://doi.org/10.1007/s00426-005-0012-8

Sakai, K., Kitaguchi, K., & Hikosaka, O. (2003). Chunking during human visuomotor sequence learning. *Experimental Brain Research*, *152*(2), 229–242. https://doi.org/10.1007/s00221-003-1548-8

Salmoni, A. W., Sullivan, S. J., & Starkes, J. L. (1976). The attention demands of movements: A critique of the probe technique. *Journal of Motor Behavior*, *8*(3), 161–169. https://doi.org/10.1080/00222895.1976.10735068

Schmidt, R. A., Lee, T. D., Winstein, C., Wulf, G., & Zelaznik, H. N. (2018). *Motor control and learning: A behavioral emphasis*. Human Kinetics.

Schmidtke, V., & Heuer, H. (1997). Task integration as a factor in secondary-task effects on sequence learning. *Psychological Research*, 53–71.

Schumacher, E. H., & Schwarb, H. (2009). Parallel Response Selection Disrupts Sequence Learning Under Dual-Task Conditions. *Journal of Experimental Psychology: General*, *138*(2), 270–290. https://doi.org/10.1037/a0015378

Shah, V. A., Thomas, A., Mrotek, L. A., Casadio, M., & Scheidt, R. A. (2023). Extended training improves the accuracy and efficiency of goal-directed reaching guided by supplemental kinesthetic vibrotactile feedback. *Experimental brain research*, *241*(2), 479-493.

Shea, C. H., Kennedy, D., & Panzer, S. (2019). Information processing approach to understanding and improving physical performance. In M. H. Anshel, T. A. Petrie, & J. A. Steinfeldt (Eds.), *APA handbook of sport and exercise psychology: Sport* *psychology* (pp. 557–582). American Psychological Association. https://doi.org/10.1037/0000123-028

Shea, C. H., Kovacs, A. J., & Panzer, S. (2011). The coding and inter-manual transfer of movement sequences. *Frontiers in Psychology*, *2*, 1–10. https://doi.org/10.3389/fpsyg.2011.00052

Shea, C. H., Panzer, S., & Kennedy, D. M. (2016). Effector Transfer. In Loffing, F. Hagemann, N., Strauss, B., MacMahon, C. *Laterality in Sports: Theories and Applications*, 179–203. Academic Press. https://doi.org/10.1016/B978-0-12-801426-4.00009-2

Spelke, E., Hirst, W., & Neisser, U. (1976). Skills of divided attention. *Cognition*, *4*(3), 215–230. https://doi.org/10.1016/0010-0277(76)90018-4

Stets, A., Smith, S. L., & Helton, W. S. (2020). Dual-Task Interference Between Swimming and Verbal Memory. *Human Factors*, *62*(7), 1132–1140. https://doi.org/10.1177/0018720819871743

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. (2020). The dual-task practice advantage: Empirical evidence and cognitive mechanisms. *Psychonomic Bulletin and Review*, *27*(1), 3–14. https://doi.org/10.3758/s13423-019-01619-4

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

Telford, C. W. (1931). The refractory phase of voluntary and associative responses. *Journal of Experimental Psychology*, *14*(1), 1.

Tombu, M., & Jolicoæur, 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. (1964). Monitoring and storage of irrelevant messages in selective attention. *Journal of Verbal Learning and Verbal Behavior*, *3*(6), 449-459.

Van Selst, M., Ruthruff, E., & Johnston, J. C. (1999). Can Practice Eliminate the Psychological Refractory Period Effect. *Journal of Experimental Psychology*, *25*(5), 1268–1283.

Verwey, W. B. (1995). A Forthcoming Key Press Can Be Selected While Earlier Ones Are Executed. *Journal of Motor Behavior*, *27*(3), 275–284.

Verwey, W. B. (1999). Evidence for a multistage model of practice in a sequential movement task. *Journal of Experimental Psychology: Human Perception and Performance*, 1693–1708.

Verwey, W. B. (2001). Concatenating familiar movement sequences: The versatile cognitive processor. *Acta Psychologica*, *106*(1–2), 69–95. https://doi.org/10.1016/S0001-6918(00)00027-5

Verwey, W. B. (2003). Processing modes and parallel processors in producing familiar keying sequences. *Psychological Research*, *67*(2), 106-122.

Verwey, W. B., Abrahamse, E. L., & de Kleine, E. (2010). Cognitive processing in new and practiced discrete keying sequences. *Frontiers in Psychology*, *1*, 1565. https://doi.org/10.3389/fpsyg.2010.00032

Verwey, W. B., Abrahamse, E. L., de Kleine, E., & Ruitenberg, M. F. (2014). Evidence for graded central processing resources in a sequential movement task. *Psychological Research*, *78*, 70-83.

Vieluf, S., Massing, M., Blandin, Y., Leinen, P., & Panzer, S. (2015). The role of eye movements in motor sequence learning. *Human Movement Science*, *40*, 220–236. https://doi.org/10.1016/j.humov.2015.01.004

Welford, A.T. (1952). The "psychological refractory period" and the timing of high-speed performance – a review and a theory. *British Journal of Psychology, 43*, 2-19.

Wickens, C. D. (1984). Processing resources in attention. In R. Parasuraman & D. R. Davies, *Varieties of attention* (pp. 63–102). Academic Press.

Wickens, C. D. (2002). Multiple resources and performance prediction. *Theoretical Issues in Ergonomics Science*, *3*(2), 159–177.

Wilde, H., Magnuson, C., & Shea, C. H. (2005). Random and blocked practice of movement sequences: Differential effects on response structure and movement speed. *Research Quarterly for Exercise and Sport*, *76*(4), 416–425. https://doi.org/10.1080/02701367.2005.10599314

Wilde, H., & Shea, C. H. (2006). Proportional and nonproportional transfer of movement sequences. *Quarterly Journal of Experimental Psychology*, *59*(9), 1626–1647. https://doi.org/10.1080/17470210500303755

Wilke, J. T., & Vaughn, S. C. (1976). Temporal distribution of attention during a throwing motion. *Journal of Motor Behavior*, *8*(2), 83–87. https://doi.org/10.1080/00222895.1976.10735058

Willingham, D. B. (1998). A neuropsychological theory of motor skill learning. *Psychological Review*, *105*(3), 558–584. https://doi.org/10.1037//0033-295x.105.3.558

Willingham, D. B., Wells, L. A., Farrell, J. M., & Stemwedel, M. (2000). Implicit motor sequence learning is represented in response locations. *Memory and Cognition*, *3*(28), 366–375. https://doi.org/10.1080/17470210902732130

Wollesen, B., & Voelcker-Rehage, C. (2014). Training effects on motor-cognitive dual-task performance in older adults: A systematic review. In *European Review of Aging and Physical Activity*, *11*(1), 5–24. https://doi.org/10.1007/s11556-013-0122-z

Woodworth, R. S. (1899). Accuracy of voluntary movement. *The Psychological Review: Monograph Supplements*, *3*(3), i–114. https://doi.org/10.1037/h0092992

Woollacott, M., & Shumway-Cook, A. (2002). Attention and the control of posture and gait: a review of an emerging area of research. *Gait and Posture*, *16*(1), 1–14.

Wrisberg, C. A., & Shea, C. H. (1978). Shifts in attention demands and motor program utilization during motor learning. *Journal of Motor Behavior*, *10*(2), 149–158.

Wulf, G., & Shea, C. H. (2002). Principles derived from the study of simple skills do not generalize to complex skill learning. *Psychonomic bulletin & review*, *9*(2), 185-211.

Yang, Y. R., Chen, Y. C., Lee, C. S., Cheng, S. J., & Wang, R. Y. (2007). Dual-task-related gait changes in individuals with stroke. *Gait and Posture*, *25*(2), 185–190. https://doi.org/10.1016/j.gaitpost.2006.03.007

Zirngibl, C., & Koch, I. (2002). The impact of response mode on implicit and explicit sequence learning. *Experimental Psychology*, *49*(2), 153–162. https://doi.org/10.1027//1618-3169.49.2.153

Appendix

Overview of further publications

Panzer, S., Haab, T., Massing, M., Pfeifer, C., & Shea, C. H. (2019). Dyad training protocols and the development of a motor sequence representation. *Acta psychologica*, *201*, 102947.

Julian, R., Skorski, S., Hecksteden, A., Pfeifer, C., Bradley, P. S., Schulze, E., & Meyer, T. (2021). Menstrual cycle phase and elite female soccer match-play: influence on various physical performance outputs. *Science and Medicine in Football*, *5*(2), 97-104.

Panzer, S., Kennedy, D., Leinen, P., Pfeifer, C., & Shea, C. (2021). Bimanual coordination associated with left-and right-hand dominance: testing the limb assignment and limb dominance hypothesis. *Experimental Brain Research*, *239*, 1595-1605.

Panzer, S., Pfeifer, C., Leinen, P., & Shea, C. (2022). Dyad Training in a Perceptual-Motor Task: "Two Pairs of Eyes Are Better Than One". *Journal of Motor Learning and Development*, *10*(2), 245-256.

Pfeifer, C., Leinen, P., Puhl, J., & Panzer, S. (2023). Visual behavior and road traffic hazard situations when using a bike computer on a racing bike: An eye movement study. *Applied Ergonomics*, *112*, 104070.

Panzer, S., Pfeifer, C., Daniel, L., Gaschler, R., Haider, H., & Shea, C. H. (2024). Across-task binding: The development of a representation in learning a continuous movement sequence. *Human Movement Science*, *94*, 103195.

Panzer, S., Pfeifer, C., Leinen, P., & Puhl, J. (2024). Visual behavior of racing bike cyclists in multi-tasking situations. *Human movement science*, *95*, 103224.

Overview of conference talks

Authors: Pfeifer, C. Panzer, S. Shea, C.

Title: “Dual-Task Training and the Development of a Sequence Representation.”

Contribution of Christina Pfeifer: Presenter

Conference: NASPSPA Conference, 2019

Authors: Pfeifer, C. Shea, C.H. Panzer, S.

Title: “Dual-task training and the development of a sequence representation.”

Contribution of Christina Pfeifer: Presenter

Virtual Conference: NASPSPA Conference, 2020

Authors: Pfeifer, C Shea, C.H Panzer, S.

Title: “The Role of Executive Functions: Single-Task vs. Dual-Task Training in Learning a Simple Movement Sequence.”

Contribution of Christina Pfeifer: Presenter

Virtual Conference: NASPSPA Conference, 2021

Authors: Pfeifer, C., Puhl, J., & Panzer, S.

Title: “Welchen Einfluss hat das gleichzeitige Monitoring der Kadenz und von Verkehrssituation auf die Einhaltung einer Zielkadenz beim Rennradfahren? ”

Contribution of Christina Pfeifer: Presenter

Virtual Conference: DVS-Conference, „Sportwissenschaftlicher Hochschultag“, 2022

Authors: Pfeifer, C., Puhl, J., & Panzer, S.

Title: “Is there dual-task interference in cycling when using bike computers?”

Contribution of Christina Pfeifer: Presenter

Conference: DVS-Conference „Sportmotorik“, 2022

Authors: Pfeifer, C., Shea, S., & Panzer, S.

Title: “Does Dual-Task Practice Influence the Temporal Change of Attention Demands of Sequence Representation?”

Contribution of Christina Pfeifer: Presenter

Conference: NASPSPA Conference, 2022

Authors: Pfeifer, C., Puhl, J., & Panzer, S.

Title: “Does a bike computer attenuate visual attention to detect hazardous traffic situations?”

Contribution of Christina Pfeifer: Presenter

Conference: NASPSPA Conference, 2023

Statutory Declaration

I hereby certify that this cumulative dissertation was written independently, without unauthorized external assistance and the use of sources or aids other than those indicated and marked as such. Additionally, I affirm that this dissertation has not been previously published or a similar form has not been submitted and evaluated elsewhere as a doctoral thesis has not been submitted and evaluated elsewhere in this or a similar form.

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