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CHALLENGES IN MOTOR SKILL CHANGE

UNRAVELING BEHAVIORAL, COGNITIVE AND ELECTROPHYSIOLOGICAL CORRELATES OF PROACTIVE INTERFERENCE

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von Laura Friederike Sperl M.Sc.
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Gutachter:

1. Prof. Dr. Rouwen Cañal-Bruland (Bewegungs- und Sportpsychologie, Friedrich-Schiller-Universität Jena)
2. Prof. Dr. Karen Zentgraf (Bewegungs- und Trainingswissenschaft, Goethe-Universität Frankfurt am Main)

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STUDY 2

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CHAPTER 1

INTRODUCTION

1 INTRODUCTION

"Change is the only constant in life." – Heraclitus

Today, more than 2000 years after the famous Greek philosopher recognized this, we encounter its truth possibly more than ever. Nowadays, in a continuously growing and progressing world, innovations in research, technology and society emerge almost every day precipitating ongoing change and accelerated development. In addition, globalization and fast communication infrastructure cause new trends and discoveries in any domain of life to spread rapidly across the globe. Following this universally increased pace in which the world is changing today, it is often not only beneficial but also indispensable to keep up with its change and adapt to the current circumstances. Inspired by the ideas of Darwin on the origin of species, Megginson (1963) acknowledges that "it is not the most intellectual of the species that survives; it is not the strongest that survives; but the species that survives is the one that is able best to adapt and adjust to the changing environment in which it finds itself" (p.4), thereby corroborating the idea that adaptation to change is inevitable. Notably, this need for change is not limited to the evolutionary context but also extends to many situations in daily life. Especially when striving for highly skilled performance, it is often advisable to keep up with new technologies and techniques to not remain left behind (e.g., Kemp & Farrow, 2006). While often being intended to raise performance to a higher level on a more or less voluntary base, a need for skill modification may also derive from changes in rules, norms or individual preconditions that cause an unavoidable need for adaptation.

However, such changes often pose a particularly tough challenge and it does not seem to be the standard to master the implied processes effortlessly. In fact, the human as a creature of habit often struggles to change a behavior which has proven to be beneficial in the past. Especially when it comes to skilled performance, pre-existing skills are usually highly automatized, making the change process even harder (Fitts & Posner, 1967). As a result, the reality is that performance often initially decreases before the intended benefits of the behavioral transformation are reached. Hence, modifying existing skills usually requires large effort and time resources and may turn out to be even harder than learning a completely novel skill (Panzer et al., 2005). As a consequence, many individuals think twice and often decide against changes when they are confronted with the voluntary decision whether or not to modify an existing skill and prefer to accept a suboptimal performance instead.

Another aspect to be drawn from the evolutionary theory is that apparently not every species is equally successful in adaptation to change (Megginson, 1963). This is not only true at the level of different species, but also within a single species. In fact, among humans there seem to be large interindividual differences in adaptability to change (May et al., 1999; Oreg, 2003), which is of central interest in Chapters 2.3, 5 and 6 of this thesis.

Importantly, since human behavior usually encompasses motor components, a motor learning and control perspective seems essential when investigating human skill change. Therefore, the main focus of the current work will lay on the modification of existing motor skills, motor behavior and goal-directed movement techniques. Despite its ubiquitous relevance, skill change and motor skill change in particular, has rarely been the focus of scientific research so far. Addressing this gap in knowledge, the aim of this thesis was to understand the cognitive mechanisms underlying motor skill change and study potential factors which might affect the success of a skill change process.

This publication-based thesis is structured into four main parts. To start with, a theoretical framework for the topic will be established (Chapter 2). Within this framework, first, a central introduction to the critical area of research will be provided in Chapter 2.1, addressing the role of motor skill change in the field of sport. Therein, challenges, reasons and objectives as well as the pivotal role of proactive interference in skill change will be introduced. In the following sections, the potential roles of action constraints (Chapter 2.2) and interindividual differences (Chapter 2.3) for successful interference control will be elaborated, before both research questions as well as the resulting work program will be outlined in Chapter 3. Chapters 4 to 7 encompass four empirical articles, each addressing the role of proactive interference along with different influencing factors on motor skill change. Specifically, the aim of the study in Chapter 4 was to investigate the potential effectiveness of a motor restriction for motor skill change. In Chapter 5, a study is presented that extended this approach by additionally examining interindividual differences which might account for the amount of interference experienced in such a motor skill change task. Chapter 6 then presents a study which focused on the critical role of inhibition and proficiency as individual factors determining the amount of interference. Finally, a fourth study investigated the relation between inhibition and interference in motor tasks by applying a neuroscientific perspective which is presented in Chapter 7.

In the last part of this thesis, the general findings of this empirical work will be summarized and discussed in Chapter 8. This discussion will involve a theoretical interpretation, a critical reflection of the methodology as well as notions on future directions regarding research on motor skill change.

CHAPTER 2

THEORETICAL FRAMEWORK

2.1 CHANGING AUTOMATIZED MOVEMENT PATTERNS

Laura Sperl & Rouwen Cañal-Bruland

PUBLISHED AS

Sperl, L., & Cañal-Bruland, R. (2020). Changing automatized movement patterns. In N. J. Hodges & A. M. Williams (Eds.), *Skill Acquisition in Sport: Research, Theory and Practice* (3rd ed., pp. 20–38). Routledge.

2.2 ROLE OF ACTION CONSTRAINTS FOR INTERFERENCE REDUCTION

2.3 INTERINDIVIDUAL DIFFERENCES IN THE AMOUNT OF INTERFERENCE

2 THEORETICAL FRAMEWORK

2.1 CHANGING AUTOMATIZED MOVEMENT PATTERNS

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2.1.1 INTRODUCTION

The development of novel training technologies forces athletes to adapt to new equipment which may require changes in their existing motor skills and strategies. Advancements in training technologies are by no means the only reason that make it necessary to change movement patterns that may have become largely automated. For example, the introduction of new rules or the surprising discovery of a novel technique that proves to be superior to established techniques may likewise force athletes to abandon movement patterns that have repeatedly resulted in success in the past, yet would likely not do so in the future (Carson et al., 2017). As a case in point, when in 1968 Richard Dick Fosbury won the gold medal in the high jump competition at the Olympics in Mexico, spectators and competitors alike were left in astonishment. Fosbury, following a curved run-up, crossed the bar backwards, a technique that had not been seen or used in competition before. At first sight, this technique, dubbed the 'Fosbury Flop', seemed strange or even awkward to the other competitors. Yet, as soon as they realized that this technique was successful, physically 'raising the bar' for the high jump, athletes all over the world started to leave behind the previously used straddle and learned the flop. After this change, the world record increased within 22 years from 2.19 m to 2.45 m (Kemp & Farrow, 2006). In other sports, similar changes have occurred such as the introduction of the V-style in ski jumping (Kemp & Farrow, 2006) or the clap skate in speed skating (van Ingen Schenau et al., 1996).

The question of how automatized movement patterns can be changed is of utmost practical importance. In this context, automaticity is defined as performing a skill "with little or no demands on attention capacity" (Magill & Anderson, 2016). In contrast to its practical relevance, research on this topic is scarce (Carson et al., 2017). As a consequence, athletes and coaches have few evidence-based principles to help guide the process of changing existing movement skills. In this chapter, we begin by clarifying issues regarding the definition of changing movement patterns. Then we critically present reasons and objectives for changing movements as well as challenges with the respective changes. We introduce and discuss four approaches to successfully guide the process of changing automatized movement patterns and provide suggestions to guide future research.

2.1.2 DEFINING CHANGING AUTOMATIZED MOVEMENT PATTERNS

One reason for the paucity of information and research regarding change of automatized movement patterns, may be that the topic is discussed under different terms in the scientific literature, including *relearning* (Musselman et al., 2016; Panzer et al., 2003), *skill transfer* (Coldwells & Hare, 1994; Mitchell & Oslin, 2006; Schmidt, 2014; Williams et al., 2003), *adaptation learning* (Roemmich & Bastian, 2015; Shadmehr et al., 1995; Sing & Smith, 2010), and *error correction* (Baxter et al., 2004; Milanese et al., 2008; Milanese et al., 2016). Notably, none of these terms covers the entire spectrum of processes involved in changing automatized movement patterns.

With respect to *relearning*, in the clinical field there are a plethora of studies which focus on the re-acquisition of skills, for example, following a stroke (D. Y. L. Chan et al., 2006; Sabari et al., 2001). In this context, relearning is concerned with reacquiring the same skills that were presumably automatized before, but it does not include a change towards a modified or new movement pattern. Second, *skill transfer* describes the degree to which the capability of performing one task contributes to performing and/or learning another task (Schmidt, 2014). For example, gymnasts may transfer their learned skill to do a kip-up on the floor (i.e., an explosive body movement from a supine position extending legs and hip to achieve a standing body position) to execute a kip on bars because both movements include similar components (Schmidt, 2014). As in this example, in skill transfer situations the task goals differ. In contrast, changing automatized skills is often concerned with situations in which the task goal remains identical, such as in the 'Fosbury Flop' scenario, where two different techniques compete to achieve the same goal. Despite this difference, transfer processes certainly form an integral part of changing automatized movement skills. Third, *adaptation learning* typically means a gradual shift in the execution of a particular motor skill which is often based on trial and error learning. For adaptation learning, learning proceeds through the repetitive evaluation of any discrepancy between a planned and desired outcome (termed internal or forward model). Usually, in motor adaptation paradigms, motor performance is experimentally perturbed such as in force-field tasks (Shadmehr & Brashers-Krug, 1997; Sing & Smith, 2010), split-belt-walking (Musselman et al., 2016; Roemmich & Bastian, 2015), or visuo-motor adaptation by means of prism glasses (Schot et al., 2017). Notably, in these paradigms the task goals remain identical across conditions (J. A. Taylor & Ivry, 2012). Changing automatized movement patterns can involve these gradual shifts, yet in sports, situations can emerge in which the previous motor pattern is just not feasible anymore and hence a gradual shift is impossible. In addition, while adaptation often refers to short-term changes as a response to situational variations, changing automatized movement patterns relates to relatively permanent and stable modifications of a motor skill. Fourth, *error correction* describes a process where an erroneous movement pattern is modified in response to feedback that there was an error (in outcome or movement form). Sometimes errors are long-lasting and highly automatized (Baxter et al., 2004; Walter & Swinnen, 1994). Athletes may often not even be aware of such habitual errors and, as a consequence, secondary, compensatory errors may develop (Milanese et al., 2016). While habitual errors represent a common cause for changing automatized motor skills, they are by no means a necessary condition as the urge to change motor skills may also be fueled by the mere intention to learn a more advanced or new technique (see later). It follows that because neither *relearning*, *skill transfer*, *adaptation learning* nor *error correction* entirely covers what changing automatized movement patterns means, a better term and operational definition is required.

A definition of 'changing automatized movement patterns' needs to capture two essential aspects. First, changing automatized movement patterns refers to the relatively permanent modification of an already existing skill. Consequently, in order to modify a particular motor skill, an already learned skill serves as a necessary pre-condition. It logically follows that the starting point for the process of changing an established skill is fundamentally different from learning a new motor skill (Carson & Collins, 2016, 2017; Panzer, 2002). Second, changing automatized movement patterns implies that the task goals remain the same. That is, despite using a modified movement pattern the task goal such as crossing the bar in high jump remains identical. We therefore propose the following definition:

Changing automatized movement patterns is the **relatively permanent modification** of an **already acquired movement pattern** while the **overall task goals** remain the same.

Unfortunately, and as opposed to, for instance, 'motor learning' or 'relearning' there is no single term to denote changing automatized movement patterns. Interestingly, this is different in other languages, such as German, where changing automatized movement patterns is covered by a single term ('Umlernen') that is used in various contexts of learning including in the context of motor learning (Panzer, 2002, 2004; Panzer et al., 2005). Sometimes *technique change* or *technical change* is used when referring to this concept in motor learning and control (Carson et al., 2014; Carson & Collins, 2011). A significant overlap exists between these two concepts and technique change is often used synonymously to changing automatized movement patterns. This seems to be particularly true when changing automatized movement patterns refers to a switch from one technique to another (e.g., from straddle to flop), but less clear when it refers to the modification of single *features* of a movement or technique (like for error correction). In the remainder of this chapter, we therefore prefer to use 'changing movement patterns' as a more fine-grained depiction of the phenomenon in question. Whenever the two can be used synonymously, we opt to do so.

How is the process of changing an already established motor skill different from learning a novel motor skill? Schmidt and Lee (2011) define motor learning as: a) a process of acquiring a motor skill; b) a direct result of practice; c) not directly observable; and d) a relatively permanent change. At first glance, all of these characteristics seem to apply equally to changing already existing movement patterns. However, the main difference between motor learning and changing an already existing movement pattern is the different starting point (Panzer, 2002). As illustrated in Figure 2-1, when changing an already established movement pattern, the existing skill is often highly practiced, performed automatically, or in other words, has reached the autonomous phase. By contrast, motor learning is assumed to start with the cognitive phase (Fitts & Posner, 1967).

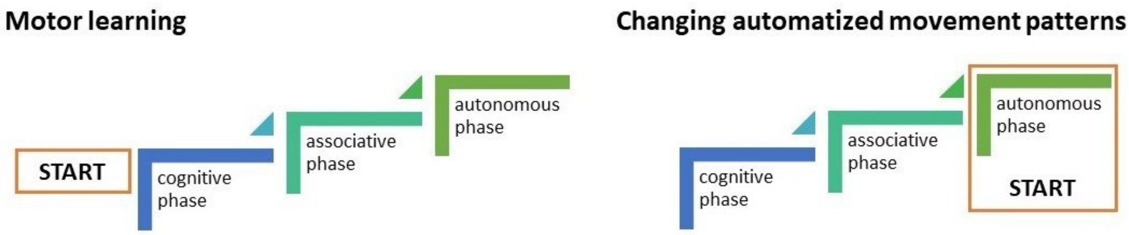

Figure 2-1. An illustration of motor learning (left) and changing automatized movement patterns (right) following the three stage model by Fitts and Posner (1967).

As depicted in Figure 2-1, in order to successfully modify an existing motor skill, the learner must first break with the automatism and exit from the autonomous stage in the learning process. We will see in this chapter that this process can be challenging. To elaborate, in the next section, we first briefly sketch the reasons as well as the objectives for and subsequently the challenges with changing existing movement patterns.

2.1.3 REASONS, OBJECTIVES, AND CHALLENGES

Reasons for changing automatized movement patterns

One obvious reason for the need to change an already existing movement pattern follows a change in the performance conditions. According to Newell's constraint-led approach, these conditions can lie in the task, in the individual or in the environment (Newell, 1986). Newell called these conditions "*constraints*", defined as factors that limit, support or form action possibilities and influence the development of movement patterns. If one of these constraints changes, an adaption of the current behavior is necessary. A change in the *task* implies, for instance, rule changes or changes to equipment (such as a new racket or differently sized ball). A change in the *individual* can be due to physical change or limitation following developmental processes or injuries. The *environment* includes all the factors surrounding the individual and contains variables such as the ground, weather and team composition (Newell, 1986). Any of these changes can result in a situation where the previous motor behavior is less appropriate or successful. Consequently, the previous, often highly automatized motor skill, must be changed. The athlete is forced to adapt to the new conditions in order to reconstruct the previous performance level or improve performance at long sight.

However, even when none of the constraints has changed, it still may be useful to change existing motor skills. For example, an athlete may be successful despite a suboptimal technique. But the current technique might limit the athlete's performance in the future (as they progress to a higher skill level or age group) or in competition under pressure. Then technique change can be useful. Also, automatized errors can be highly problematic. Walter and Swinnen (1994) referred to "bad habits" when discussing errors that have become permanent parts of one's motor repertoire. The reason why the errors become habitual is often due to the fact that the athlete still manages to execute the movement successfully by including compensatory movements, which decrease the direct impact of the error (Milanese et al., 2016). Such automatized errors may hamper performance and increase the risk of injury. Therefore, coaches need to be sensitive to these types of errors and intervene as early as possible as the long-term consequences are not always conspicuous to the athletes.

Objectives underpinning the need to change

A central question concerning the aims of changing already existing movement patterns is whether the new technique should replace the original one or if both motor programs should (and can) coexist in the future. Carson and Collins (2011) refer to these processes as *shift* (replacement) and *bifurcation* (coexistence). A replacement is always desirable when the original movement pattern is not useful anymore (which is often the case in technique change or error correction). However, especially for the situation of temporary changes to constraints/ conditions, it can be useful to retain the original movement pattern. For example, when an athlete switches from indoor to beach volleyball, the overall task goals remain similar, yet there may be change in environmental constraints (e.g., weather) or task constraints (e.g. rules, ball size or type). Yet, whether the athlete regularly switches between indoor and beach volleyball or abandons the indoor career to exclusively push a career in beach volleyball makes a difference. Coexistence may be useful in the former scenario, whereas replacement may be strived for in the latter. In this context, it is important to note that it remains unclear whether it is even possible to extinguish or overwrite an original motor program at all (Epstein, 1972).

Challenge: Performance decrements and proactive interference

Changing motor skills is often instantiated with the aim of enhancing athletic performance. On the playing field, however, the change of an already acquired movement pattern is frequently accompanied by initial performance decrements (Carson & Collins, 2016; Panzer et al., 2005). It takes time and effort to regain the original performance level, before performance eventually improves beyond previous levels. Another problem is that even if the new way to execute a motor skill starts to result in superior performance under training conditions, it may not immediately do so in competition (e.g., it may not yet be robust against pressure). It seems justified to say, although perhaps counterintuitive, that changing an existing skill can be harder than learning a new skill, precisely because athletes *cannot* start from scratch (Panzer, 2002).

Why might it be so hard to change an existing, automatized motor skill? A key mechanism accounting for this problem is *interference,* the overlay of new memory contents and existing old memory contents. Transfer can occur in a positive (transference) or negative manner (interference), thus facilitating or impeding performance respectively. Moreover, it can be forward-directed (proactive) or backward-directed (retroactive) (Magill, 2007; Pöhlmann, 1994; Schmidt, 2014). When experiencing performance decrements, the old, automatized and still dominant movement pattern competes against the new, to-be-acquired movement pattern, resulting in proactive interference (Baxter et al., 2004; Mühlbauer & Krug, 2007; Panzer et al., 2005). This kind of interference can disturb both the acquisition and recall of new memory contents (Tempel & Frings, 2016), especially when situations are similar and cues for the old behaviour are active (Loft et al., 2008; Schmidt, 2014; Underwood, 1957). This is, for instance, the case when an athlete has just started to use the flop instead of the straddle in high jump, but the situation still triggers the use of the to-be-replaced technique and hence interferes with it, resulting in initial performance decrements (note, however, that positive transfer is also possible, see e.g., Mühlbauer & Krug, 2007).

To study the role of proactive interference in changing existing movement patterns, Panzer (2002) designed an experiment using a force parametrization task. The general idea was to compare two groups on the same test, and to beforehand let one group practice with a slightly modified task to examine proactive interference. During the testing, participants of both groups had to perform a monopedal vertical jump task with a horizontally fixed board under the right foot, simulating the push-off phase in speed skating. The test included 10 blocks of

10 trials each with the instruction to reproduce exactly submaximal jump heights at 60% of their previously determined individual maximal jump height. Whereas one group (i.e., the control group) was exposed to the task for the first time during testing, the experimental group had performed the same task under slightly different conditions 48 hours before. During this pre-session the board under the foot was shifted backwards so that the toes exceeded the board by 25 mm, thereby minimally varying the biomechanical demands of the task. Finally, 48 hours after the main test both groups performed a retention test including one block of 10 trials. The experimental group reproduced their individual target jump heights more exactly (depicted as lower absolute errors in Figure 2-2) when compared to the control group in the first trials of the main test. This seemed to suggest positive transfer in the experimental group. However, this advantage disappeared over the subsequent blocks resulting in performance levels similar to the control group. In the retention test, the experimental group performed significantly worse than the control group. It seems that proactive interference hampered retention of the acquired skill.

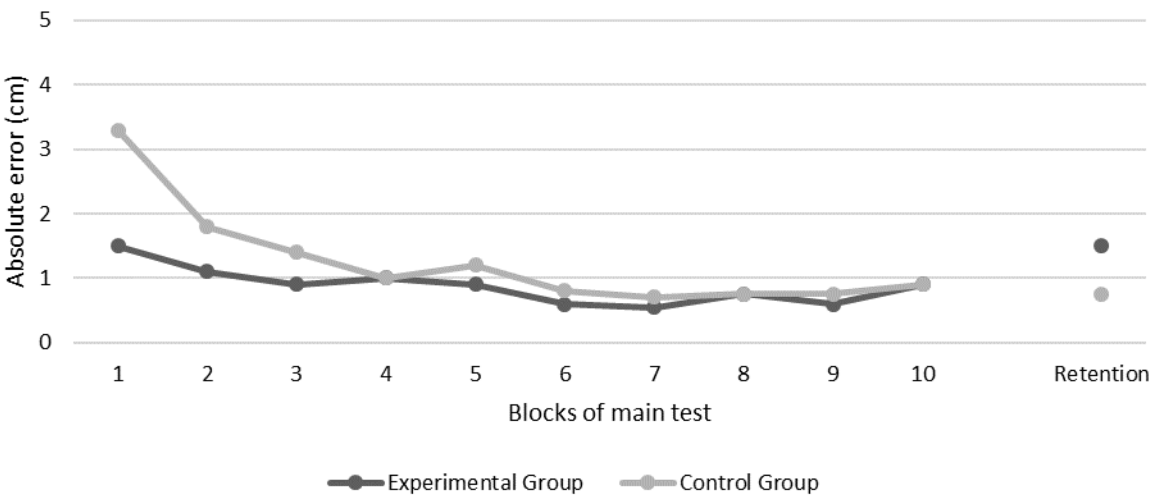

Figure 2-2. Results adapted from Panzer et al. (2002) depicting absolute errors pertaining to the test goal of 60% of maximal jump height. The test consisted of 10 blocks of the main test performing the monopedal jump and a 48 hr retention test for both groups. Note the experimental group had previously practiced this task under adapted conditions with different take off constraints 48 hr previously.

In a related study, a similar experimental set-up and design was employed to test whether and to what degree the temporal distance between the practice of two similar skills impacts performance and retention of a second skill (Mühlbauer & Krug, 2007). Similar to Panzer et al. (2002), after initial positive transfer effects, the retention test revealed proactive interference effects in terms of poorer performance in the group that had to modify their movement pattern. This interference effect occurred regardless of the temporal distance between the two practice conditions (2.5 or 24 hours). Taken together, these studies suggest that proactive interference may be a key challenge for changes in automatized skills.

2.1.4 INTERVENTION APPROACHES

To the best of our knowledge, four approaches have been proposed to successfully achieve and guide the process of changing automatized movement patterns. These include: 1) the Method of Amplification of Error; 2) the Old Way New Way approach; 3) the Five-A Method; and 4) Directed Forgetting. In this section, we briefly introduce each approach and discuss the empirical support for each.

Method of Amplification of Error

Whereas many motor learning methods are based on delivering external feedback by direct instruction or demonstration, the 'Method of Amplification of Error' (MAE) targets *internal feedback* processes in order to enhance the individual's ability to detect the correct movement on their own (Milanese et al., 2008). The basic idea of MAE is that the learner must amplify the error and then recognize how the motor action needs to be changed. The role for the coach is to first identify the primary error in the athlete's movement. According to Milanese and colleagues, there is always a principal error, that is, one which primarily affects outcome, in contrast to secondary errors which derive from compensatory adjustments (Corte et al., 2015; Milanese et al., 2008). Because compensatory movements often allow for relatively accurate movement execution, errors may not be corrected and therefore can be long-lasting and become habitual. Once the primary error is identified, the coach provides the athlete with an instruction that leads to an exaggeration of the erroneous movement. After successful execution of this error amplification, the athlete can then start to correct the motor action, this being a reiterative process.

Several researchers have tested this approach in the context of motor learning (Y.-C. Chen et al., 2017) as well as in different sports such as golf (Milanese et al., 2016), tennis (Cesari &

Milanese, 1995), weightlifting (Milanese et al., 2017) and standing long jump (Milanese et al., 2008). Milanese et al. (2016) compared MAE with direct verbal instruction and no instruction (control group) in improving the golf swing of golfers with different skill levels. A proficient coach first defined critical features and elaborated technical errors of each participant's swing. Following a pre-test, the MAE and direct verbal instruction group received standardized verbal feedback on their movement from the coach. Subsequently, these participants had a free trial in which they were asked to perform the movement freely without any constraints or feedback. This procedure (feedback and subsequent free trial) was repeated three times during the training session. The control group was instructed to simply do their best. In the MAE group, participants were instructed to amplify the erroneous movement whereas participants in the direct verbal instruction group were provided with corrective feedback on what to change to approach the optimal technique. After the training session, post and retention tests (one week after the post-test) were conducted. Performance measures were the club head speed and ball speed, which are considered the best predictors of driving swing performance. Both MAE and direct verbal instruction led to a significant improvement in these measures when compared to the control group, but MAE showed steeper learnings curves (i.e., faster and larger improvements) than the direct verbal instruction group. This difference between the groups remained present on the retention test.

By amplifying the error, MAE seems to trigger a positive search strategy and provides information about the erroneous movement and its consequences, thereby improving the individual's error detection capability and performance. Whereas in many situations MAE may offer a viable approach, it should be noted that in some situations coaches and athletes need to carefully assess whether amplifying errors could carry potential risks such as injuries. Evidence for the positive effects of MAE stems from a small number of research groups and hence awaits replication to provide further evidence for the method's viability and robustness.

Old Way New Way

The 'Old Way New Way' method for error correction was originally developed by Lyndon (1989) and has been applied not only in the sports context, but in various fields of teaching skilled behavior (Baxter et al., 2004). In particular, this method addresses so-called *habit errors* that occur when a performer executes an action incorrectly and this incorrect execution has become habitual or automatic (Baxter et al., 2004; Walter & Swinnen, 1994). Like MAE this technique guides the athlete to explicitly focus on the error.

The Old Way New Way method is an approach that directly targets the proactive interference problem. To reiterate, when changing erroneous automatized (i.e., old) movement patterns, the old habitual memory contents and hence movement patterns interfere with the to-be-learned (i.e., new) contents and patterns. Since performance is often highly cue-dependent, individuals can have a tendency to revert back to the established movement pattern which often has been practiced over years ("old habits die hard", Baxter et al., 2004, p. 27). To resolve this conflict of proactive interference, the proponents of the Old Way New Way method argue that the performer must become aware of their own erroneous performance and learn to successfully discriminate a correct from an incorrect execution. The help of a coach is said to be crucial in this process (Lyndon, 1989).

The Old Way New Way intervention is described in three different phases. In the preparation phase, the individual learns to discriminate the old from the new way. The action must be broken down into its minimal units in order to elaborate to which detail of the movement the correction must be directed towards. The learner then labels the original version explicitly as the "old way". In the mediation phase, which is in fact at the core of this method, the individual learns to contrast the old from the new way. After re-eliciting the old way of performance, the learner starts to perform the new way. The performer is instructed to explicitly name and to reflect upon commonalities and differences between the old and new way. It is suggested to repeat these three components (i.e., re-eliciting the old way, performing the new way, and reflecting on similarities and differences) of the mediation phase five times. During this process, the individual becomes progressively able to articulate similarities and differences between the two alternatives. The third phase contains the generalization and application of the newly developed skill. This phase is common to any other method of learning, where learned contents are practiced, repeated, stabilized and consolidated (Lyndon, 2000).

This method was tested in an education setting where adolescent students were executing various types of handicraft such as hammering nails and cutting glass etc. (Baxter et al., 2004). Teachers identified typical errors in students' skilled performance which met certain criteria (e.g., affected performance and progress, persistent, resistant to correction by conventional means, providing a discrete measure of performance, not too complicated to produce the new way). After four days of intensive training for teachers and observers, a pre-test was conducted to determine baseline performance (consisting of a 30-90 min observation, revealing a percentage of correct out of total attempts). This pre-test was followed by the treatment which occurred in three different conditions: Old Way New Way (as described in the previous section according to Lyndon, 2000) vs. conventional treatment (correcting errors by a conventional re-teaching approach) vs. control group (no error correction). During that session and three post-tests in weekly intervals, observers rated students' performance and behavior in all phases of the experiment. Criteria of performance were error rates (measuring procedural improvement), time to criterion (acceleration of learning) and persistence of any learning improvements (stability of learning). Additional data from observation and interviews yielded information on self-detection of errors, self-correction and teachers' and students' reactions to the training.

As depicted in Figure 2-3, the Old Way New Way intervention revealed a large improvement in performance (80 % and higher), accelerated learning, a permanent change with no requirement for further correction and also improvement across a broad range of skilled performance. It was superior to the conventional treatment and the control group. Improvements in the Old Way New Way group remained stable in all three post-tests up to several weeks later and students' reactions were widely positive (Baxter et al., 2004).

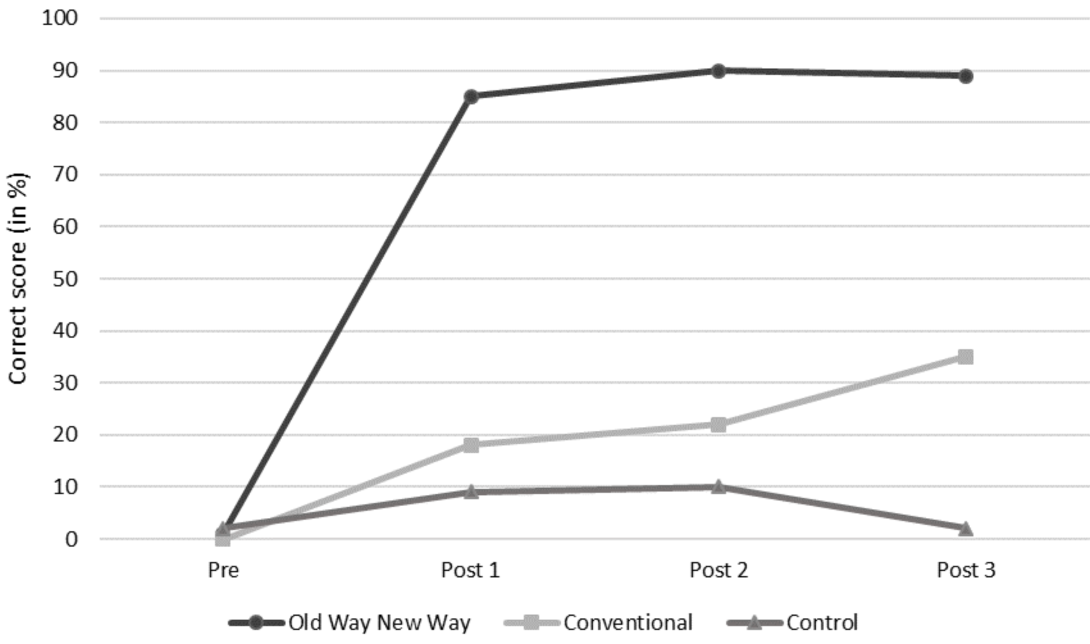

Figure 2-3. Results adapted from Baxter et al. (2004) depicting percentage of correct scores during the four test sessions for the three experimental groups.

Initial attempts to apply this method in sports seem promising. In two case studies, Hanin and colleagues reported the method to be successful after only one training session with two Olympic athletes in javelin and sprint respectively (Hanin et al., 2002) and one Olympic-level athlete in swimming (Hanin et al., 2004). In the latter case study, the swimmer sometimes jumped up too high from the starting block resulting in a deep dive and a poor glide to the surface afterwards. Applying the Old Way New Way method, the coach and athlete first elaborated a detailed analysis of the technical error. Based on this analysis and sport-specific recommendations, an individual Old Way New Way protocol was devised for the intervention session. This intervention lasted 90 minutes (including warm-up) and included the following four steps (Hanin et al., 2004): (1) improvement of the athlete's mental and physical awareness of the old and (2) the new way, (3) progressive and systematic discrimination of both ways and (4) practice or generalization of the new way. The athlete's self-reports after each start in the training session revealed gradual increase of error awareness and developing awareness for the correct movement. Also, he became more self-confident and enthusiastic from trial to trial. Most importantly, performance improved enormously. Before the intervention, the athlete performed about 40 to 50% starts correctly in training and competition. In a post-test, two days after the intervention, the amount of correct starts was 100% in training and 85% in competition three days later. Several follow-up tests, up to 8 months after the intervention, revealed 83 to 100% of correct starts. Thus, in this case, the Old Way New Way method helped to produce immediate and long-lasting changes of habitual errors (Hanin et al., 2004).

To summarize, the Old Way New Way method builds on the idea of contrasting the old, habitual technique with the new, corrected technique. Whenever errors are internalized and interference is likely to occur between the old and the new movement pattern, proponents strongly advise to use the Old Way New Way method of error correction (Baxter et al., 2004; Lyndon, 2000). Yet, despite the few promising findings, empirical evidence to support the Old Way New Way method is still scarce. The existing evidence is based on studies with small numbers of participants and sometimes on anecdotal reports and subjective observations. We therefore concur with Beek (2012) who argued that an objective assessment as to whether the method is a valid and reliable tool to successfully change automatized (erroneous) movement patterns is still missing. There is a need for randomized controlled studies. In addition, a further limitation of the Old Way New Way method is that the new technique needs to be executable quite quickly (and/or easily) which might cause a problem for applying this technique when learning complex sport movement sequences.

Five-A Method

Before outlining the main steps of the 'Five-A Method', it should be noted that Carson and Collins (2011) generally discriminate between two types of technical change. First, the process of *refinement* describes the acquisition of a technique which in at least some aspects is new to the athlete (e.g. due to changed equipment or technical innovations). Second, *regaining* reflects the correction of an erroneous or suboptimal technique (e.g. due to error acquisition or injury) by often going back to an earlier stage of learning when the motor action was more effective. To briefly reiterate, changing an already acquired technique then can take place via the gradual change from the old to the new (shift) or the establishment of a new movement pattern (bifurcation). According to the authors, a shift leads to greater initial accuracy, but is not as stable as the bifurcation method (Carson & Collins, 2011).

To successfully manage the process of change of an already established motor skill, the authors developed the step-by-step Five-A model (Carson & Collins, 2016), see also Table 2-1 and Figure 2-4. To break the automatism of old, autonomous movement patterns, similar to the Old Way New Way method, athletes first need to understand the need for change and learn to discriminate the new desired technique from the old one (Analysis). They need to call the actual movement pattern into consciousness (Awareness) and then modify the required aspects of the current technique (Adjustment). Finally, athletes must internalize the changed aspects (Automation) to further promote an autonomous and robust motor skill (Assurance).

Table 2-1. The Five-A Model according to Carson and Collins (2016).

PHASE	CONTENT
1) ANALYSIS	identification of the athlete’s requirement (i.e., which aspect of the current technique needs to be changed and further securing of the athlete’s intention to change)
2) AWARENESS	de-automation of the erroneous/to-be-adjusted technique
3) ADJUSTMENT	modification of the erroneous/to-be-adjusted technique
4) (RE)AUTOMATION	internalization of the changed aspects
5) ASSURANCE	promoting the development of automaticity also for conditions of pressure such as competitions

Figure 2-4 (adapted from Carson & Collins, 2016) illustrates how performance is typically affected over time when progressing through the five stages. As depicted, when applying a technique change, performance usually decreases initially and must be well stabilized after the achieved new performance level is reached (Panzer, 2002).

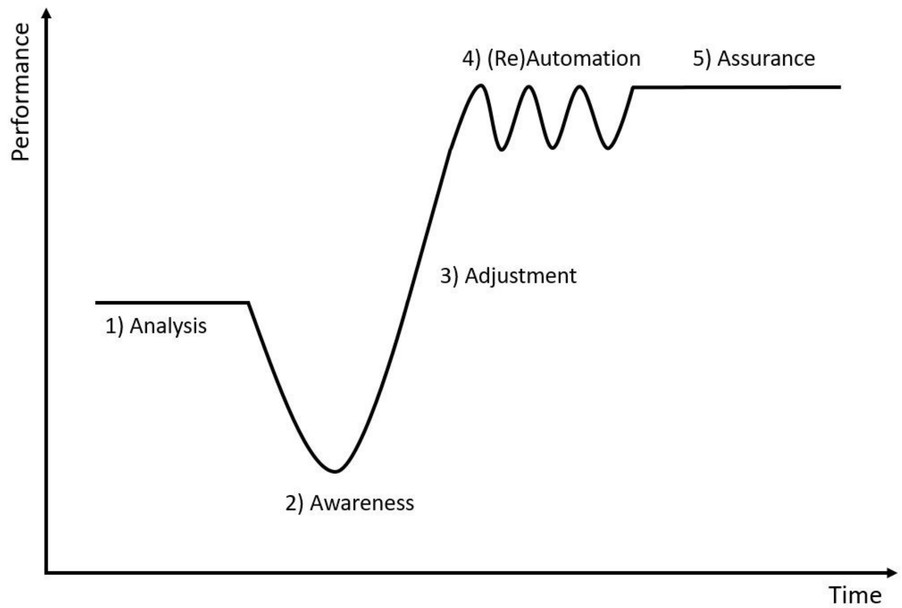

Figure 2-4. The different stages of the Five-A Method (adapted from Carson & Collins, 2016).

Several case studies have been conducted to test the Five-A method. For instance, the Five-A method was tested in a ten week intervention with an Olympic weightlifter, which also included mental imagery in the change process (Carson et al., 2014). This athlete aimed to change his technique due to an injury which resulted from a long-term technical fault. In stage one (Analysis), the problem in the current movement pattern was analyzed. The athlete had to first re-experience the erroneous movement pattern. To not risk getting injured again, instead of a weight lifting bar a broomstick was used. Then a more effective and less dangerous technique was shown and executed to promote the athlete's awareness and cues for the different sensations and positions. In the second stage (Awareness), the athlete was instructed to execute correct and incorrect lifts using a 20 kg bar, highlighting the kinaesthetic differences between the two lifts. The athlete also consulted experts about his injury in order to improve confidence and build an action plan. Stage three (Adjustment) focused on the use of mental skills for the technical change. Visual and kinaesthetic imagery were initiated and video feedback showing best trials was given to enhance confidence. In the fourth stage ((Re)Automation), the weight of the bar was gradually increased. This process was included in the imagery script. In the last stage (Assurance), the maximal weight was used and competitive simulations were included in the imagery script, serving as pre-event preparation. Video and kinematic feedback was given. Approximately one and two years later, follow-up tests revealed significant technical improvements, reduced pressure in the injured limb and improved performance, with the athlete reaching his personal best two years after the intervention (Carson et al., 2014; Carson & Collins, 2011).

To summarize, in a similar manner to Old Way New Way, the Five-A Method is based on the core idea that athletes need to learn to explicitly discriminate the new desired technique from the old one. Perhaps one of the major benefits of the Five-A Model is the fine-grained and stepwise guide through different stages of the process of change. This may be particularly informative for coaches and athletes and relatively easy to implement. However, as with the Old Way New Way method, empirical support stems mainly from case studies (Carson & Collins, 2015), and thus more randomized, controlled studies are needed to assess the method's validity and reliability.

Directed Forgetting

The final method 'Directed Forgetting' is based on the reasoning that in order to successfully execute a movement, we must retrieve the right memory content underlying the motor action. Our mind is full of stored memories and sometimes retrieval is impeded when either the wrong memory content is remembered or when several stored memories are too similar and cannot be distinguished from each other. This results in interference, that is, two memory contents compete against each other which can hamper retrieval or encoding of new contents (Tempel & Frings, 2016). Directed Forgetting is a technique aimed at reducing this interference by telling participants to simply forget the previously learned contents (Bjork et al., 1968; Bjork, 1970; Burwitz, 1974). Studies on Directed Forgetting have classically used paradigms examining the learning of word stimuli (Dreisbach & Bäuml, 2014; Festini & Reuter-Lorenz, 2014; Wylie et al., 2007) and only rarely involved motor tasks (Burwitz, 1974). There is evidence that intentional forgetting of actions is more difficult than for verbal stimuli (Earles & Kersten, 2002). Tempel and Frings (2016) recently tested this method in a motor sequence task and showed that it can help to reduce interference, at least for just learned contents. Two experimental groups practiced key sequences on a computer keyboard. In a first session, each group learned five sequences demanding three fingers of their right hand. In the second session, a new key sequence was learned. The so called "remember group" was told that they were now continuing with the second part of the experiment, whereas the "forget group" was instructed to forget the key sequences learned in the first session as they were only for warm-up. The forget group outperformed the remember group in re-enactment of the second learned sequence. In a second experiment, these authors also showed reduced recall performance for the first sequence in the forget group. Directed Forgetting enhanced both *recall* and *acquisition* during the second learning phase.

There is too little evidence to say whether Directed Forgetting is helpful in changing automatized complex motor skills in sports. However, given these initial positive findings on motor sequence learning, we suggest that researchers should scrutinize whether Directed Forgetting is applicable in sports and whether it could perhaps become a viable alternative or add-on to other methods of technique change to successfully change previously acquired movement patterns. Perhaps Directed Forgetting may become most useful once the athlete has reached a stage in the process of changing an automatized movement pattern in which he/she is consciously aware of the 'bad habit' or error.

2.1.5 INTERIM CONCLUSION[1]

In this chapter, we provided a definition of 'changing automatized movement patterns'. We then discussed the reasons, objectives and challenges for changing such movement patterns, with a particular focus on the proactive interference problem. We discussed four candidate approaches to solve these challenges. A commonality between most of these approaches is the assumption that it is necessary to break the automatism by explicitly guiding the individual's focus to (aspects of) the old movement (note that this is not necessarily the same for Directed Forgetting). Deconstructing the old, automatized behavior and starting to modify it, is often the first necessary step for changing already existing skills and reduce interference. While there is promising evidence for the Method of Amplification of Error (MAE), its generalizability to other tasks and situations awaits further confirmation. The evidence speaking for the Old Way New Way approach and the Five-A Method has sometimes shown large performance improvements, yet, and this holds true for both approaches, the evidence is based mostly on case studies. A strong scientific assessment of the validity and reliability of either approach remains to be delivered. The finally presented method, that is, Directed Forgetting, has a long-standing history in psychological research, but has not yet been examined in the context of motor performance (with a few exceptions). While the initial evidence reveals promise, it remains to be determined whether the findings transfer to more complex sport behaviors.

Several factors have not been addressed in the aforementioned approaches, but may nonetheless play critical roles in overcoming unwanted proactive interference. These factors may reside in the individual such as executive functions (e.g., working memory, task switching or inhibition capabilities), age or expertise (Brevers et al., 2018). Given large interindividual differences, it is likely that interindividual interference-proneness (May et al., 1999) may act on processes underlying the change of automatized movement skills. Therefore, there will be a

[1] Note that in the original chapter this section is entitled „Conclusion and future directions", but was changed here for the current thesis for reasons of readability and structure.

need to study how these factors impact on the process of change. Furthermore, factors influencing interference can reside in the task or environment. This affords the opportunity to manipulate directly individual, task and environmental features with the aim to reduce proactive interference. Such features could be the similarity between desired and unwanted behaviors (Underwood, 1957), the temporal distance between the initial learning and the change process of a movement pattern (Mühlbauer & Krug, 2007; Shadmehr & Brashers-Krug, 1997) or the individual's action possibilities which can be, for instance, restricted by task, environmental or individual constraints (Gray, 2018; Sperl & Cañal-Bruland, 2020c). Future research is needed to examine these potential influencing factors and identify further variables which might reduce interference.

In conclusion, there can be no doubt that changing automatized movement patterns is a highly relevant field of research and that coaches and athletes alike deserve more evidence-based guidance to support the process of technique change and performance enhancement. As it stands, the Method of Amplification of Error, the Old Way New Way approach and the Five-A Method have been applied successfully in sports. While from a scientific point of view more randomized, controlled studies are needed to assess each of these methods' validity, reliability and generalizability, all three methods provide inspiration, guidance and hence a good starting point to practitioners including coaches, teachers and athletes who wish or face the need to change automatized movement patterns.

2.2 ROLE OF ACTION CONSTRAINTS FOR INTERFERENCE REDUCTION

As described in the previous chapter, performance decrements associated with skill change usually emerge due to proactive interference caused by the pre-existing skill. It was outlined that using constraints might be one way to reduce this interference (Gray, 2018). Therefore, the present chapter aims to elaborate the role of action constraints as a potential strategy to reduce this interference and provide illustrations from the field of motor learning and control where action constraints are already implemented into practice.

When dealing with interference in motor tasks, strong, automatic response tendencies from the old behavior often compete with the new and therefore still weaker action alternative (Baxter et al., 2004; Panzer, 2002). In order to select the right action, a main challenge is to suppress the irrelevant but possibly more salient option. Based on the phenomenon of concurring alternatives, the question arises whether interference can be reduced when the unwanted movement option causing the interference is eliminated. More specifically, the idea of the present approach is that successful skill change may be facilitated when a competing alternative is withdrawn, insofar that the undesired option can physically simply not be performed anymore. Further, this method should save crucial time resources, since undesired movements are immediately physically stopped the moment they are initiated. In fact, this approach is somewhat unique for *motor* skill change where such a reduction of individual degrees of freedom may be realized, for instance, by means of action constraints such as motor restrictions.

A common example for applying motor restrictions comes from the medical field and involves the treatment of overstrain or inflammatory processes as is the case, for example, for tenosynovitis – also known as typewriter's cramp (Seiffert et al., 2020). One of the most common interventions is to reduce any further strains on the irritated tendon and thus minimize any stressing movements of the wrist (Buchhorn & Ziai, 2009). Since it is nearly impossible to cognitively implement the permanent avoidance of wrist movements, the affected joint is usually immobilized with a bandage (Buchhorn & Ziai, 2009; Mayer & Siems, 2019). This motor restriction actually follows the same logic as described above. Indeed, very probably, a strong automatic tendency to move the wrists and fingers in a habitual manner still exists. However, by immobilizing the respective wrist and physically ruling out the option to move it, the competing motor alternative cannot be executed anymore. This in turn, reduces the need for continuous cognitive control, further facilitating the cure process (Diday-Nolle & Reiter Eigenheer, 2019). Hence, by limiting the degrees of freedom and preventing unwanted alternatives, the individual is pointed towards the desired, beneficial behavior. Presumably, this approach might also be promising for error correction, concretely when individuals struggle to get rid of bad habits which cannot be suppressed successfully (see also Walter & Swinnen, 1994).

A related notion can be drawn from Bernstein (1967) who explicitly states the problem of an extreme abundance of degrees of freedom when performing a goal-directed action which is particularly demanding for novices. According to Bernstein (1967), the successful co-ordination of a movement and its improvement is achieved by mastering redundant degrees of freedom of a moving body part. Interestingly, and tying in with the evolutionary perspective in Chapter 1, some species handle this problem using a strategy called *muscular locking*, which eliminates degrees of freedom which are not necessary in a given moment. This phenomenon is observable in many invertebrate or lower forms of vertebrate species such as birds, lizards or insects which often remain immobile as statues in the intervals between two voluntary movements. In humans or other mammals, however, "in the norm there is no rest" (p. 108) and outside of deep sleep no similar immobility is present (Bernstein, 1967).

Even though action constraints are already present in several motor contexts in the applied field, as we will see later in this chapter, theoretical and empirical evidence for this approach with regard to interference control and skill change is scarce. However, concerning motor learning, the idea of action constraints is put in practice by the *constraint-led approach* (CLA; see e.g., Davids et al., 2008) for example. While the theory behind this method is also based on the idea of intentionally establishing constraints to guide motor performance, the CLA partly pursues a slightly different goal; that is the idea of self-organization (Davids et al., 2008; Lee et al., 2014). This approach is based on the idea that there are always multiple ways to achieve the same goal and that there is no optimal technique for a goal-directed action in motor control (see also the idea of nonlinear pedagogy and degeneracy; Lee et al., 2014). Importantly, constraints are not necessarily understood as limiting factors, but as task-dependent conditions that can limit, form or support action options (Newell, 1986). Consequently, applying constraints is supposed to force performers to flexibly adapt to changes by finding individual solutions and thus explore their personal scope of action. In CLA interventions, these constraints are typically manipulated to influence and guide processes of motor learning (for an overview, see Davids et al., 2008). Importantly, these constraints do not prescribe a specific movement solution, rather – by (temporarily) excluding familiar solutions – they cause the performer to develop own new movement solutions, thereby promoting self-organization. For instance, it has been shown that varying the size of the playing field or number of players in team sports, i.e. the density (Timmerman et al., 2017), or size of equipment such as racquets (Farrow & Reid, 2010) can improve learning and/or performance. Therefore, training with constraints can involve the maintenance of a certain constraint for a certain period, like is done when downscaling equipment in children's sport (for a review, see Buszard et al., 2016), but often also consists of a continuous variation of constraints. For example, Davids et al. (2008) illustrate a case where a barrier combined with different task instructions is used in soccer to constrain an athlete in such a way that she needs to search for adequate body positions and foot placement in order to solve the task. By being forced to flexibly adapt to repeatedly changing constraints, this method aims to extend an athlete's movement pattern and motor repertoire.

While this method has been widely applied in the context of motor learning and skill acquisition (Clark et al., 2019; Davids et al., 2003; Davids et al., 2008), to our knowledge, so far only one study (Gray, 2018) systematically investigated this approach explicitly in the context of motor skill change. The aim of this investigation was to optimize a technique change in baseball batting by identifying the most successful of three intervention methods (comparing CLA with external and internal attentional focus intervention). 42 skilled players with previously identified suboptimal batting techniques trained for six weeks with a baseball simulator with the aim to increase their launch angle. Prior to this intervention, they were informed about the goal of this intervention, which was to implement the fly ball technique (which enables larger launch angles). Whereas participants in the focus intervention groups received concrete instructions which guided attention towards either internal features or external effects of movement, athletes in the CLA intervention trained under a different condition. That is, in contrast to the other two training conditions, they had to hit the ball over an obstacle which was repeatedly moved in its distance to the athlete (hence constituting a constraint that was continuously varied). This method was meant to enable participants to generate own perceptual-motor solutions and expand their range of action possibilities. Importantly, while in the other two conditions concrete instructions on how to implement the fly ball technique were provided, participants in the CLA group did not receive any information about an optimal technique. The intervention revealed the CLA and the external attentional focus intervention to be superior to internal attentional focus intervention, thereby providing initial evidence towards the effectiveness of CLA for skill change (Gray, 2018).

However, as mentioned above, this approach differs in some crucial aspects from the idea of action constraints as a potential strategy for interference reduction, as was described in the beginning of this chapter. First, the CLA predominantly uses constraints to widen the scope of action and promote self-organization (Davids et al., 2003; Davids et al., 2008). While an exploration of *various individual solutions* might certainly also be a useful tool for motor skill change processes (Gray, 2018), action constraints in the present approach are intended to function in a different way. Namely, the aim of using constraints for interference reduction is to rule out *one particular undesired* motor behavior. Consequently, the respective constraint is typically implemented once and is then not varied. Hence, a constraint in our approach is mainly used to guide performers towards a specific new technique. Indeed, in skill change often two concrete solutions compete against each other – the old and the new way (see also Baxter et al., 2004). For instance, when performing a technique change in sports, athletes are actually already aware of what technique they are changing to (Panzer, 2002) since the state of the art often offers an optimal movement technique (such as Fosbury Flop biomechanically enabling greater jump heights than the straddle technique). If one agrees that such a (current) movement optimum exists, narrowing the range of action alternatives might indeed be a useful tool in this case.

It should be noted that constraints in the CLA also offer the opportunity to reduce the range of possible options and remove certain movement solutions that do not work well (Davids et al., 2008). However, as explicated above, whereas the focus of the CLA is on the exploration of new strategies, the focus of using constraints for interference control is mainly on the avoidance of an undesired strategy. Thus, as mentioned in the introductory example of a medical wrist bandage, the constraint actually limits the degrees of freedom in order to disable execution of undesired motor actions. In the following, we will have a more detailed look at where and how constraints can be implemented for interference control in skill change.

In Chapter 2.1, where we already introduced constraints as possible causes for the necessity for skill change, we also broached the issue that constraints are usually classified into three different categories (see subsection *Reasons for changing automatized movement patterns*). This tripartite division claims that constraints are inherent either to the individual, to the task or to the environment (for a detailed description, refer to Chapter 2.1 and also Newell, 1986). Since environmental constraints involve external factors that normally cannot be manipulated by the experimenter or coach (Newell, 1986), action constraints as interventions mainly derive from the individual and task category. What these constraints look like and how widely the approach of action constraints is already applied as a tool to eliminate undesired behavior in the field of sports will be illustrated by the following examples.

Constraints immanent to the *individual* are often applied directly "at the body" of an individual, this way restricting the degrees of freedom of movement effectors. In sports, such a constraint is used in bowling for example, where many expert players use a specific bandage in order to prevent their wrist from bending during approach and release of the bowl (D. Taylor, 1980; Werner, 1996). Skilled players are also able to avoid this bending with the right technique, however, this bandage facilitates the optimal execution and lends additional stability, preventing overstrain and injury (Duda, 1988).

According to Newell (1986), *task* constraints involve manipulations of rules, goals, or equipment. A good example of sports equipment functioning as motor restrictions can be seen in the newest technology of exercise machines in the gym. When, for example, performing supine bench presses, traditionally the barbell is pressed up as a free weight. However, an essential challenge in this exercise is to stabilize and balance the bar and lift it in a vertical path over the chest which is particularly demanding for novices or patients in rehabilitation who lack technical experience and the required neuromuscular conditions, or even for experienced athletes suffering from fatigue at the end of a training session (Schick et al., 2010). A wrong technique may not only reduce the effectiveness of this exercise, it also poses a high risk of injury if the barbell suddenly runs out to one side (Maud & Foster, 2006). Alternatively, athletes can also perform fixed-form exercises, i.e. using certain exercise machines which enable them to execute exercises in a more guided manner (Cotterman et al., 2005). A common example (also applicable to supine bench presses) is the so-called *Smith Machine*. This is a machine where the barbell can no longer be moved completely freely where both ends are attached to two vertical guiderails, thereby ensuring that the barbell is always lifted vertically on a fixed path and cannot drift out of this dimension, promoting a proper lifting technique (Cotterman et al., 2005; Kuvačić et al., 2017). Furthermore, integrated safety lockouts in the rack enable the athlete to rest at any point if necessary, preventing the bar from falling uncontrolledly. Hence, by restricting the athlete's range of motion, detrimental behavior is prevented (Cotterman et al., 2005). This example illustrates well how motor restrictions can also be implemented by reducing the degrees of freedom in motion by manipulating equipment rather than individual constraints.

Notably, task constraints may also be implemented beyond the manipulation of equipment by adding tools to the task which are not originally task-inherent. An example of this is the usage of obstacles which block certain movements or routes in locomotion. This is implemented, e.g., in long jump training by placing an obstacle right after the take-off to force athletes to increase the height of their flight phase (American Sport Education Program, 2008). Another example is the correction of suboptimal running paths which may be detrimental in choreographic sports or team sports by simply forcing athletes to bypass this object, thereby promoting a desired route in locomotion (Davids et al., 2008; Dicks & Chow, 2010).

Importantly, exemplifications are not limited to the domain of sports. Motor restrictions are already implemented in other fields such as human engineering or rehabilitation with the aim of avoiding detrimental motor behavior. Examples vary from ergonomic tools, such as chairs which force individuals to adopt a healthy upright body position while sitting (e.g., Bettany-Saltikov et al., 2008; Cho et al., 2015), over orthopedic devices, such as back corset preventing harmful postures (e.g., Klausner, 2018), through to modern exoskeletons provided to factory workers that promote healthy postures, assist in straining positions or indicate unhealthy postures via tactile feedback (e.g., Carrozza et al., 2019; Zhang et al., 2016).

To sum up, it is surprising how widely – despite the lack of scientific evidence – action constraints are already used to facilitate motor skill change in various fields of application. However, some questions remain; for example, what happens after the removal of an action constraint. Some constraints are designed to stay implemented without need for future removal, whereas others are intended to provide only temporary support. It is also uncertain whether the reported advantages transfer to all individuals and all situations involving motor skills. From a scientific point of view, more randomized controlled trial (RCT) studies are needed to assess this method's validity, reliability and generalizability and to examine this approach in more detail in the future. In order to provide an initial attempt to do so, one of the aims of this dissertation project was to systematically study the role of action constraints for interference control and scrutinize the effectiveness of this approach for motor skill change. This has been done in the studies presented in Chapters 4 and 5 where the effectiveness of a motor restriction as a support to prevent undesired movement tendencies due to strong automatisms was investigated.

2.3 INTERINDIVIDUAL DIFFERENCES AFFECTING THE AMOUNT OF INTERFERENCE

In addition to task manipulations, such as the use of constraints to reduce interference in motor change processes, it was outlined in Chapter 2.1 that individual factors might also determine the success of a change process. As proactive interference is assumed to constitute a key mechanism accounting for the extent of performance decrements, it seems promising to have a closer look at the roots of interindividual differences in interference.

Studies investigating concepts such as individual *interference susceptibility* (e.g., Bowles & Salthouse, 2003; Earles et al., 1997; Hedden & Yoon, 2006) or *interference proneness* (e.g., Lustig et al., 2001; May et al., 1999) find a high variance across individuals regarding the extent to which participants are affected by interference. Often, this phenomenon is examined utilizing word learning paradigms (e.g., Kane & Engle, 2000; Rosen & Engle, 1998); that is, participants are asked to memorize word lists that are presented either visually or auditorily. This learning phase is usually followed by a distraction task, before participants are instructed to retrieve words from certain previously learned lists while suppressing (similar) content from currently irrelevant others (Fernandes & Grady, 2008; Kane & Engle, 2000). The difficulty of these tasks increases the more interfering information is present, that is, e.g., the more (semantically similar) lists or words are learned the more difficult the retrieval task becomes (May et al., 1999; Underwood, 1949, 1957). The concept of interference susceptibility within these tasks describes that participants' performance declines to different extents (Earles et al., 1997; Hedden & Yoon, 2006; May et al., 1999). In other words, some participants seem to overcome the interference quite well, whilst others suffer more this cognitive overlap.

In this context, several cognitive functions have been reported to be associated with the amount of interference, e.g. working memory (Bowles & Salthouse, 2003; Earles et al., 1997; Hedden & Yoon, 2006), task-shifting (Hedden & Yoon, 2006), perceptual speed (Earles et al., 1997) and inhibition (Earles et al., 1997; Hedden & Yoon, 2006; Levy & Anderson, 2002). Since these tasks often consist of the aforementioned word learning paradigms and thus require oral responses, they do not feature motor skills per se. Moreover, these tasks almost never address a pre-existing, automatized skill. Rather, participants in these studies learn something ad-hoc in the lab, such as skills or stimuli that are exclusive and specific to the task (e.g., Kane & Engle, 2000; Koedijker, Oudejans, & Beek, 2010; May et al., 1999; Underwood, 1949). Therefore, the question arises which variables may determine the amount of interference when changing already existing motor skills. In the following, three candidates which are likely to be able to explain differences in the amount of interference in motor tasks will be described.

2.3.1 EXECUTIVE FUNCTIONS

Executive functions are often classified into three core functions, which are working memory, cognitive flexibility and inhibition (Diamond, 2013; Miyake & Friedman, 2012). Each of these core functions is conceivable to be involved in motor skill change. Since cognitive flexibility includes the ability to see issues from different perspectives, think creatively and to quickly and flexibly adapt to new situations, task demands or priorities (Diamond, 2013), one might consider this function to be beneficial for any kind of skill change process, as changes require new or adapted solution strategies. Working memory describes the ability of "holding information in mind and mentally working with it (or said differently, working with information no longer perceptually present)" (Diamond, 2013, p. 142). As skill changes often require keeping new rules and the information about changed conditions and corresponding responses cognitively present in mind (especially when no motor restrictions are available, see Chapter 2.2), a higher working memory capacity might also be beneficial for successful motor skill change. In addition, it is conceivable that a higher working memory capacity enables a less salient new action option to co-exist cognitively next to a strong one. Finally, as elaborated in Chapter 2.2, an essential challenge when dealing with interference is to suppress an irrelevant but possibly more automatic action option. Thus, and perhaps most importantly, it seems plausible that especially inhibitory processes are required in these situations and account for successful skill change.

Indeed, the concepts of interference and inhibition are closely linked to each other and inhibition is known as a useful tool for interference control (Dempster & Brainerd, 1995). Empirical support for the claim that previous memory traces are inhibited when they are replaced by newer, more relevant ones stems from the retrieval-practice paradigm for example, as described, e.g., in Levy and Anderson (2002). In the reported experimental paradigm participants learn pairs of words. After this learning phase, the first item of each pair is coupled to a new target item. In other words, the second item of a pair is replaced by a new word. Hence, a new word pairing needs to be learned and recalled. In a later test, recall performance for these replaced stimuli is compared to control stimuli. Poorer recall performance is usually observed for the replaced stimuli in comparison to stimuli which were not practiced at all. This phenomenon supports the assumption that no longer relevant stimuli are not only attempted to be forgotten but are intentionally inhibited (Levy & Anderson, 2002).

Nevertheless, the relationship between interference and inhibition seems to be "far from straightforward" (Stoltzfus et al., 1993, p. 186). Mixed findings (e.g., M. C. Anderson & Neely, 1996; Earles et al., 1997; Levy & Anderson, 2002; Stoltzfus et al., 1993) might be (at least partially) due to the fact that in its long-standing research history, inhibition has often been treated as a unidimensional construct. However, in the past decades, growing evidence has been reported that there is not just one single type of inhibition. It rather seems to represent a multidimensional construct and should be classified into different dimensions (Rey-Mermet et al., 2018). One prominent approach to subdivide inhibition is provided by Friedman and Miyake (2004). Based on the original ideas by Nigg (2000), the authors postulate three different dimensions:

First, *resistance to distractor inhibition* describes the ability to ignore irrelevant information from the environment, such as distractor stimuli known from, e.g., negative priming tasks (Fox, 1995) or flanker paradigms etc. (Eriksen & Eriksen, 1974; Fox, 1995). Second, *resistance to proactive interference* comprises the ability to resist internal memory contents, which were relevant in the past but are no longer relevant, such as in the word-pairing task by Levy and Anderson (2002). The third and last dimension is *prepotent response inhibition* and involves the ability to suppress strong action tendencies and automatic behavior. This is, e.g., the case when resisting the strong tendency to read out a word instead of naming its color in the well-known Stroop Task (Stroop, 1935).

Following this classification, the additional question arises which of these subdimensions may be able to explain the amount of interference in motor skill change. Whereas typically no specific distractor stimuli are inherent in skill change tasks, it is conceivable that one must resist interference from the internal knowledge about the previous execution of a task. Moreover, resisting automatic behavioral tendencies in order to execute the required action seems to be crucial and hence prepotent response inhibition might be particularly relevant for change tasks in the motor domain. Therefore, one might assume that especially resistance to proactive interference as well as prepotent response inhibition might be involved in situations where automatized motor skills need to be changed.

Importantly, the term or concept of inhibition includes both a general *cognitive ability* as well as a *cognitive control process* operating in a specific situation. This leads to two assumptions with regard to the relationship between interference and inhibition. On the one hand, and in the context of interindividual differences, we would anticipate better inhibitory abilities to be associated with less proactive interference. Within this relation, inhibition represents a general cognitive ability which functions as an individual beneficial pre-requisite (similar to the variables age and proficiency which are described in the following subchapters). Such a relationship should, for instance, be observable via correlations between inhibition test scores and the extent of performance deterioration in motor skill change. It could hence be investigated via cognitive and behavioral testing (see Chapters 5 and 6).
On the other hand, inhibition also represents a cognitive process. Following our reasoning from above, we would therefore, in turn, expect inhibitory processes to be at play in situations of interference control. Gaining insight into the cognitive control processes engaged in a particular situation is certainly more difficult, but thanks to modern neuroscientific measuring technology it is not impossible. In this context, EEG is a useful tool which provides a time-precise online assessment of the electrophysiological activity during a certain task. One technique here is to analyze event-related potentials (ERPs). Since different cognitive mechanisms are known to elicit specific characteristic ERP patterns, we can generate assumptions about which cognitive processes are involved in a certain task (Luck, 2014). Hence, if it is true that inhibitory processes are required for successful interference control, this might be visible in specific ERP patterns which are suggested to reflect inhibitory processes (Luck, 2014; Xie et al., 2017; see Chapter 7).

In conclusion, with inhibition representing both a cognitive process as well as a cognitive ability, the relation between inhibition and interference is likely to be in some sense bidirectional[2]. Importantly, within our research framework, this constellation calls for different methodologies, which are illustrated in Figure 2-5. In fact, this thesis employed a two-step approach. In a first

[2] Note that "bidirectional" here does by no means refer to claims regarding causality, but rather serve as a tool in order to describe the underlying conceptualization of both methodological approaches (see also Figure 2-5).

step, the individual inhibition abilities were measured by administering well-established cognitive tests (Friedman & Miyake, 2004). It was then investigated whether higher test scores were associated with less interference within a motor skill change task which is intentionally designed to induce proactive interference (Chapters 5 and 6). We reasoned that if it indeed would turn out that higher inhibition abilities go along with less interference, we would, in turn, observe inhibitory processes to be at play in situations of interference control. This was then tested in a second step which investigated the relation from the reverse direction (see Chapter 7). Specifically, we again administered a motor skill change task which is designed to induce interference. However, we now used EEG to measure the electrophysiological activity pattern that occurs in situations of successful interference control. Based on the existing literature, the observed ERP pattern was hypothesized to deliver insight into the cognitive mechanisms at play during these situations of interference control (for detailed information, see Chapter 7).

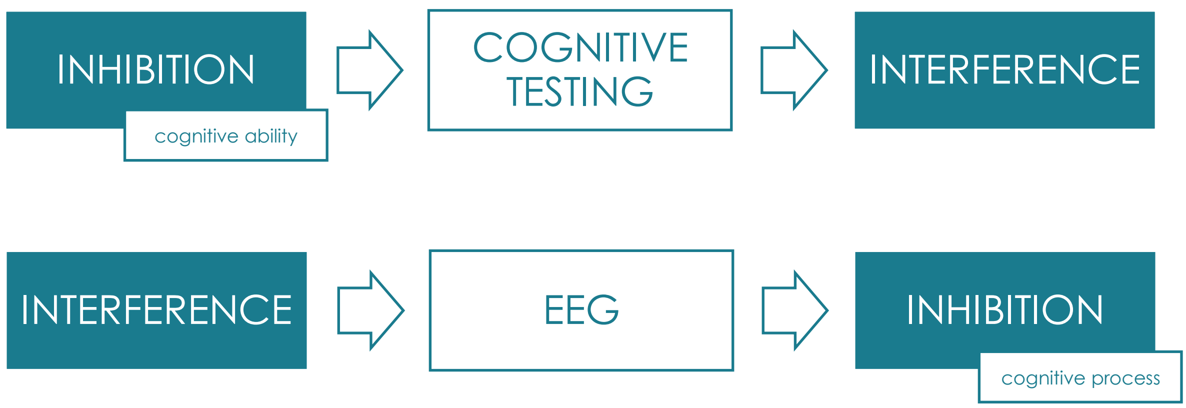

Figure 2-5. Schematic illustration of the relation between inhibition and interference (dark boxes) and the corresponding methodology (white boxes). Top: Inhibition is measured as a cognitive ability via cognitive testing. The assessed test scores may then be associated with the extent of interference that occurs in a motor skill change task. Bottom: Interference is intentionally induced with a motor skill change task. EEG activity is analyzed for trials demanding interference control. Characteristic electrophysiological patterns may then provide information about the involved cognitive processes.

2.3.2 AGE

The role of inhibition for interference susceptibility becomes even more pronounced when looking at age differences. Many cognitive abilities are known to decrease with age, and so do inhibitory abilities (for an overview, see Bialystok & Craik, 2006). Notably, it is often assumed that many age-related deficits in cognitive functioning are caused by impairments in the suppression of irrelevant information (May et al., 1999). According to the inhibition deficit hypothesis, much of the decline in cognitive functioning can be attributed to decreasing abilities of older adults to suppress or ignore irrelevant thoughts and actions (Hasher & Zacks, 1988; Lindfield et al., 1994). Reduced inhibitory abilities are suggested to result in difficulties to notice relevant information, switch attention and control access to working memory (Hasher & Zacks, 1988). Lustig et al. (2001) argue that age differences in working memory are not caused by capacity differences but due to differences in overcoming interference. This is in line with other research reporting a higher susceptibility to interference in older adults (e.g., Bowles & Salthouse, 2003; Earles et al., 1997; Lustig et al., 2001). Hence, both inhibitory as well as interference control abilities seem to account for efficient information processing and are not stable over the lifespan and in fact are subject to age-related declines (Adólfsdóttir et al., 2017; Bowles & Salthouse, 2003; Earles et al., 1997; Nielson et al., 2002; for reduced interference resistance in early childhood, see also Dempster & Brainerd, 1995). However, evidence regarding this age-related decline is not always convergent and contrary findings have also been reported (e.g., Brache et al., 2010; Rey-Mermet et al., 2018). In a meta-analysis including 176 studies, Rey-Mermet and Gade (2018) recently provided evidence that decreases in inhibitory abilities appear to be highly task- or dimension-specific. More specifically, their analysis revealed that impairments are often found for response inhibition, whereas other inhibitory dimensions remain unaffected, calling for additional need to treat inhibition as a multidimensional construct as proposed earlier in this section.

Assuming that prepotent response inhibition plays a critical role in motor skill change and that susceptibility to interference increases with older age, it is conceivable that motor skill change also becomes more difficult with increasing age. As empiric studies on motor skill change are scarce in general, the question to what extent inhibitory abilities and age may predict successful motor skill change awaits empirical testing. Therefore, the study presented in Chapter 5 addressed the relationship between age and proactive interference.

2.3.3 PROFICIENCY

Finally, in addition to general cognitive abilities, a very skill-specific factor appears likely to be associated with the amount of interference. This is proficiency and refers to the degree of mastering a skill before the critical change. In simple words, one could ask: Who struggles more with the challenges posed by skill change – experts or novices? As randomized, controlled studies on skill changes are rare, the question whether a high proficiency in a skill is beneficial or detrimental when this skill is changed, to our knowledge, has not been investigated so far. Since empirical evidence is lacking to generate expectations, it is useful to have a look at theoretical models from the field of motor learning to approach this question.

In Chapter 2.1 we already introduced the three-stage model of learning by Fitts and Posner (1967). We claimed that one of the main challenges in regard to changing already existing movement patterns is that the learner has often already reached the autonomous phase of skill acquisition. Hence, in contrast to learning a novel skill the learner usually does not start from scratch (Panzer, 2002) but starts with a highly automatized movement skill (see Figure 2-1). The main challenge of skill change now consists in the necessity to break the existing automatism before being able to start modifications. As proactive interference emerges from strong, pre-existing skills, it is likely that interference is particularly strong when previous skills are highly automatized and promote behavioral tendencies associated with that skill (see Chapter 2.1). Since, in turn, skilled behavior is often characterized by automatization (Fitts & Posner, 1967), it might be assumed that a high proficiency is detrimental for skill change and therefore, especially those individuals whose pre-existing skills are strongly automatized experience large interference (see also Chapter 2.1). In fact, elite athletes have often been often the subject of interest in a series of case studies on motor skill change (e.g., Carson & Collins, 2015; Hanin et al., 2004).

However, this theory is in contrast to other prominent theories of motor learning, which postulate that proficiency is also characterized by the ability to flexibly adapt to changed conditions (Ericsson, 2008; Gentile, 1972). Based on these theories, experts should outperform novices not only regarding the skill per se, but also when it comes to changes. In his work on deliberate practice, Ericsson (2008) claims that expertise is characterized by never completely reaching the autonomous (automatic) phase of motor learning, and instead actively engaging in continuous evaluation, feedback, problem-solving and performance refinement. According to Ericsson (2008), achieving the autonomous phase is only advisable for everyday activities whereas regarding complex skills, experts counteract automaticity and maintain continuous cognitive control over the skill (see also Figure 3 in Ericsson, 2008). Also from the CLA perspective, according to Davids et al. (2013), expertise is understood “as the individual’s capacity to functionally interact with key constraints” (p. 23f).

Besides this skill-specific role of proficiency, higher executive functioning or better inhibitory abilities are sometimes reported in top athletes (e.g., Brevers et al., 2018; J. Chen et al., 2019; Heppe & Zentgraf, 2019). As a consequence, some experts might also benefit from a sport-unspecific advantage in executive functions which again may also be beneficial for motor skill change.

In conclusion, different prominent theories of motor learning seem to make different predictions about the success of motor skill change depending on skill proficiency. Thus, it remains to be determined whether a high proficiency regarding a certain skill is beneficial or detrimental when this skill needs to be changed. This issue has been addressed by the empirical work presented in Chapters 5 and 6.

CHAPTER 3

RESEARCH QUESTIONS, EXPERIMENTAL PARADIGM AND WORK PROGAM

3 RESEARCH QUESTION, EXPERIMENTAL PARADIGM AND WORK PROGRAM

Despite its ubiquitous relevance, the topic of motor skill change has barely been in the focus of scientific research in the past (see Chapter 2.1). The aim of this dissertation is to contribute to and raise attention for this field of research by attempting to unravel mechanisms underlying successful motor skill change. Specifically, the concept of proactive interference as well as the resulting performance decrements associated with change processes will be scrutinized and hence are of central interest. Given the potential use of action constraints (Chapter 2.2), the conceivable impact of interindividual differences regarding executive functions (Chapter 2.3.1), age (Chapter 2.3.2) and proficiency (Chapter 2.3.3), four empirical studies will be presented that focus on the role of action constraints (Chapters 4 and 5) and interindividual differences (Chapters 5, 6 and 7) for motor skill change.

In order to study automatized motor skills, we therefore first developed an experimental paradigm, which was applied in each of the different studies of this dissertation project. Whereas many of the previous studies examined proactive interference by letting the participants acquire a certain motor skill or sequence in the lab and then modify this just-learned skill (e.g., Koedijker, 2010; Panzer, 2002), we opted to investigate a motor skill that is already automatized by the participants prior to the experiment (thereby additionally aiming to raise the ecological validity by approaching motor skill change as it generally occurs in real life). Specifically, our paradigm involved the skill of typing on a computer keyboard, which constitutes a complex motor skill involving different effectors (Yamaguchi, 2019). Examining the skill of typing actually offers some kind of button-press task while maintaining a high ecological validity (Kalfaoğlu et al., 2018). As a central part of work and everyday life, typing is mastered and frequently used by a large amount of the population nowadays and typically relies on highly automatized and proceduralized knowledge (Logan, 2018). This proved to be beneficial in several ways: On the one hand, this motor skill allowed us to quantify motor performance relatively easily by measuring errors and reaction times (thereby even being able to assess subcomponents of a movement sequence), which are well-defined performance indicators that are directly associated with the skill per se. On the other hand, this paradigm gave us the possibility to induce proactive interference by confronting the participants with different types of rule changes which affected parts of their familiar movement patterns and thus was able to immediately disrupt participants in their automatized motor behavior. Importantly, the motor skill of typing was designed to serve as a kind of proxy in the attempt to approach the involved mechanisms when changing automatized movement patterns in general.

In our empirical work, we pursued different methodological approaches. First and foremost, the application of the typing paradigm as a motor skill change task and the associated performance assessment were central parts of each of the studies. Furthermore, we also collected additional behavioral data by conducting several cognitive tests (Chapters 5, 6 and 7) as well as by assessing gaze behavior via eye-tracking technology (Chapter 5). Finally, we extended our approach by administering electroencephalography (EEG) to explore the electrophysiological correlates of interference control in motor skill change and gain insight into the neuro-cognitive mechanisms at play during interference control (Chapter 7). Motivation for these different methodological approaches as well as the article-specific research aims always resulted from the findings, limitations and prospects of each previous study. The following chapters (Chapter 4 to 7) will now present the four scientific peer-review articles containing the empirical studies which arose from this dissertation project.

CHAPTER 4

REDUCING PROACTIVE INTERFERENCE IN MOTOR TASKS

STUDY 1

Laura Sperl & Rouwen Cañal-Bruland

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4 REDUCING PROACTIVE INTERFERENCE IN MOTOR TASKS

ABSTRACT

Changing automatized movement patterns often leads to initial performance decrements caused by proactive interference. In this study, we scrutinized whether proactive interference could be reduced by inhibiting the to-be-changed movement pattern by means of a physical movement constraint and verbal inhibition instructions, and whether any of the two interventions may be superior. Skilled typists typed short texts as fast and accurately as possible on a regular QWERTZ keyboard. After baseline measures, a new rule prohibiting the use of the left index finger was introduced. Subsequently, participants took part in either a verbal instruction or an additional motor restriction intervention phase. Results revealed that the original rule change was successful in inducing proactive interference in skilled typists. Most importantly, the two interventions similarly reduced proactive interference both immediately following the rule change and after ten practice sessions. We conclude that reducing proactive interference by means of physical motor restrictions and verbal instructions may be equally effective.

4.1 INTRODUCTION

Skilled motor performance is characterized by a high degree of automatization (Fitts & Posner, 1967). Even though the aim of skill acquisition and motor learning often is to achieve the execution of highly automatized movement skills that are, among other things, characterized by fast and fluent movement execution, little demands on working memory and attention etc. (Fitts & Posner, 1967; Schmidt & Lee, 2011), highly automatized skills can become particularly problematic when the movement or parts of the movement need to be changed.

Such a need to modify an already established motor skill can, for instance, often be witnessed in sports where, due to technical progress in terms of new tools or new techniques (Kemp & Farrow, 2006; Newell, 1986) or the necessity to correct movement errors (Baxter et al., 2004; Milanese et al., 2016; Walter & Swinnen, 1994), athletes have to change automatized movement patterns. Usually, the aim of such a change is either to enhance or to re-establish previous performance levels. However, the process of change often seems to disadvantageously result in initial performance declines (Carson & Collins, 2016). One reason for this initial performance deterioration consists in the fact that the to-be-changed, established movement pattern hampers or interferes with the acquisition or recall of the new, to-be-established motor skill (Tempel & Frings, 2016). This phenomenon is referred to as *proactive interference*. In more general terms, proactive interference refers to a situation in which individuals experience a forward-directed overlapping of old, existing memory contents with new, to-be-learned memory contents, especially when both contents are relatively similar (Radvansky, 2017). As a result of limited memory capacity (Koedijker, Oudejans, & Beek, 2010), stored memory contents and to-be-learned information compete against each other and impede consolidation and/or retrieval of the relevant contents (Edwards, 2011; Tempel & Frings, 2016; Underwood, 1957). It follows that only once performers learn to control, regulate and reduce interference, performance will start to improve again.

Thus far, our understanding of the mechanisms underlying proactive interference has been mainly informed by memory research (Dempster & Brainerd, 1995; Underwood, 1957). Fundamental memory research has significantly increased our knowledge about the processes driving proactive interference (Dempster & Brainerd, 1995; Underwood, 1957), related variables (Jacoby et al., 2010; Kane & Hasher, 1995; May et al., 1999; Shadmehr & Brashers-Krug, 1997) and the effects caused by proactive interference (Ascoli & Schmidt, 1969; Friedman & Miyake, 2004; Jacoby et al., 2010). Yet, surprisingly little research has been dedicated to the role of proactive interference in the domains of skill acquisition and motor learning (Koedijker, Oudejans, & Beek, 2010; Panzer, 2002; Shadmehr et al., 1995). In one of these mentioned exceptions, Panzer (2002) applied a monopedal vertical jump task and found initial proactive facilitation from one motor skill to a similar one. However, in a subsequent retention test proactive interference led to decrements in the secondly performed motor skill, indicating that proactive interference may have hampered the retention of the second skill (Koedijker, Oudejans, & Beek, 2010; Panzer et al., 2003; Shadmehr et al., 1995).

Given the unwanted detrimental performance effects caused by proactive interference in motor learning in general and when changing automatized movement patterns in particular, the question arises how proactive interference can be effectively reduced. Here we suggest that one potential answer to this question and hence way to reduce proactive interference is to learn to inhibit the established memory contents associated with the automatized movement pattern. In fact, the ability to control memory contents is driven by executive control processes (Levy & Anderson, 2002). In particular, *inhibitory control* seems to play a pivotal role in overcoming competition between two or more memory contents (Friedman & Miyake, 2004) (M. C. Anderson, 2003). In so-called "response-override situations" (Levy & Anderson, 2002) individuals are required to suppress a habitual response to a certain stimulus as the situational demands call for a different stimulus-response-association than usual (as, for instance, in the well-known Stroop Task; Stroop, 1935). Because the old association is often stronger, proactive interference arises and hampers novel stimulus-response associations. One cognitive strategy that has been shown to resolve this conflict is to inhibit the habitual response in order to focus on the adequate response (for empirical support, see M. C. Anderson et al., 1994). This method is supposed to limit the influence of simultaneously activated and distracting memories (Levy & Anderson, 2002).

According to Chiappe et al. (2000), the process of inhibition can operate in different ways and involves three core functions: (1) *access* - by preventing irrelevant information from accessing working memory; (2) *deletion* – by suppressing or removing irrelevant contents from working memory; and (3) *restraint* – by preventing strong prepotent responses and action tendencies. Here we reason that for motor inhibition processes involved in changing automatized movement patterns, the *restraint* function may be of particular relevance. If true, then constraining motor processes by rendering the execution of unwanted action response tendencies impossible may, in fact, facilitate inhibition. To test this, we borrowed ideas from Newell's constrained-led approach (Newell, 1986) and examined whether motor inhibition by means of an action constraint may successfully reduce proactive interference. Next to addressing the potential benefit of using a physical motor restriction, this study aimed at scrutinizing whether reducing proactive interference by means of verbal instructions alone may or may not be similarly effective in reducing proactive interference.

In specific, concerning the *access* and *deletion* function, we argue that verbal instructions that cognitively suppress response tendencies with the aim to inhibit certain behaviours might impose relatively high demands on working memory capacity. This may be different for the *restraint* function though. It is reasonable to assume that an external motor restriction requires less working memory load as it already prevents the execution of prepotent response tendencies, thereby eliminating prohibited or unwanted action options. If this logic is sound, then an additional motor restriction may facilitate the reduction of proactive interference when changing automatized movement patterns beyond mere cognitive inhibitory processes. However, in case changes of motor patterns are mainly driven by cognitive inhibition (including *access* and/or *deletion*), then verbal inhibition instructions alone may be as effective as additional motor restrictions in reducing proactive interference. To test this corollary, in this study skilled touch-typists had to overcome and reduce proactive interference induced by a rule change, and were therefore subjected to two intervention groups, i.e., a verbal instruction group and an additional motor restriction group. The rule change introduced after baseline measures meant that participants were no longer allowed to use the left index finger for typing. In line with our reasoning and based on Chiappe et al. (2000), in the verbal instruction group the rule change ("you are no longer allowed to use the left index finger") demanded from the participants to either prevent the original action option (typical use of the left index finger) from accessing working memory or, in case it accessed working memory, to suppress or remove it (deletion function). Again, in keeping with our theoretical reasoning, the motor restriction applied in the additional motor restriction group may eliminate or at least reduce the need to suppress prepotent response tendencies (i.e., the urge to use the left index finger) while in the verbal instruction group this urge needed to be cognitively suppressed.

4.2 METHODS

PARTICIPANTS

22 skilled touch-typists (7 male; mean age: 31.86, *SD* = 8.36) which met the criterion of a minimum typing speed of 50 words per minute (WPM) (Yamaguchi & Logan, 2014) participated in the experiment. Mean typing speed was 67.4 WPM (Range: 50 – 98.2), on average they used touch typing for 16.82 years (*SD* = 7.27). They were randomly assigned to one of two equally sized experimental groups (verbal instruction group vs. additional motor restriction group; both *N* = 11). All participants were native speakers (German) and affiliates (secretaries, academic staff or students) of the Friedrich Schiller University Jena who typed regularly in their

professional life on computer keyboards (mean typing frequency 4.4 on a scale from 1 *never* to 5 *always*). The experiment was approved by the Ethics committee of the Faculty of Social and Behavioural Sciences of the Friedrich Schiller University Jena.

DESIGN

The idea and benefit of using touch-typing was that (a) participants possessed an already automatized skill (as opposed to Panzer, 2002), (b) performance measures were quantifiable (e.g., total time, interkeystroke interval etc.), (c) proactive interference could be induced by experimental manipulation (i.e., through a rule change), and (d) a motor restriction could be applied to prevent movement execution. Skilled touch-typists were asked to first type short paragraphs as fast and accurately as possible without any constraint, applying the regular touch-typing system. Subsequently, they were forced to change their familiar movement pattern by following a novel rule that did not allow them to use their left index finger for typing. Participants were then randomly assigned to two groups and practiced this new rule in an intervention phase. Whereas the *verbal instruction (VI) group* practiced following the verbal instruction of the new rule only, the *additional motor restriction (AMR) group* received an additional motor restriction which made it physically impossible for participants to use of the left index finger during training. Performance was compared in both groups before, during and after the intervention phase.

MATERIALS

The experiment took place on a desktop computer (Fujitsu Celsius M740) with an external monitor (Fujitsu P24W-7, size: 24 inch) and a standard German QWERTZ keyboard. A software was programmed with Python to present stimulus sentences and measure typing performance. Correctly typed characters were highlighted in green; in case of a typing error the background colour of the corresponding characters transformed into red signalling the typist to correct the last entry by pressing the correct key to continue. The software recorded the total time, the Interkeystroke Interval (IKSI), typing speed and errors.

In order to ensure typing flow and trigger automatized finger movement behaviour, we decided to use real sentences as typing material. To this end, participants had to type short paragraphs of three German sentences during the experiment (see Appendix 4-A). All paragraphs had comparable characteristics and a considerable percentage of left index finger keys (main text: 37 words, 259 signs, 21.2 % left index finger keys; transfer text 1: 37 words, 260 signs, 21.9 % left index finger keys; transfer text 2: 40 words, 262 signs; 0 % left index finger keys). Paragraphs consisted of grammatically correct German sentences and included only letters and no special signs apart from dot and comma. Content, however, was unrelated and irrelevant.

Figure 4-1 shows the finger bandage (HailiCare) which was used as a motor restriction. It was fastened on the left wrist and could be individually adjusted to fixate the left index finger of each participant.

Figure 4-1. Finger bandage used as a motor restriction for left index finger.

An online exit questionnaire was programmed using the online platform Sosci Survey. It assessed demographic data as well as other relevant information regarding the experiment such as typing experience etc.

PROCEDURE

On arrival at the lab participants were informed about the procedure by the experimenter and provided informed consent. The experiment then started with a short warm-up in order to familiarize participants with software, monitor and keyboard. In that session, they typed six sentences of prose, before performing two trials of familiarization with the main text which constituted the stimulus material for Baseline, Rule Change, Intervention and Post-Test. With the aim to observe learning curves and to exclude any influence of stimulus difficulty on performance, we decided the stimulus material to remain the same for these tasks (A. M. Anderson et al., 2009; M. C. Anderson & Green, 2001; Gordon et al., 1994; Parasher et al., 2001). Task instructions were given in written form right before each block. Participants started each typing task manually when they were ready. They subsequently performed the different blocks with the instruction to type as fast and as accurately as possible. One block involved typing the corresponding paragraph once.

Baseline. In the Baseline block, participants typed the first paragraph *(main text)* without any constraint applying the familiar touch-typing system.

Rule Change. In the next block, the critical rule change was introduced to the participants in order to disrupt the automatized typing behaviour. From now on, they were not allowed to use the left index finger anymore for further typing. According to the touch-typing system, this affected the key presses of the letters R, F, V, T, G and B which now had to be pressed by another finger. Any breach of rule (i.e., typing a letter with the left index finger despite of the new rule) was indicated by the experimenter by an auditory signal. Participants were instructed to avoid abducting the left index finger when applying the rule but leaving it normally on the keyboard.

Intervention Phase. The experiment applied a between-subject design and compared two groups in the intervention which included ten practice blocks. Whereas the VI group received only the verbal instruction to continue with the rule change, the AMR group practiced in the subsequent blocks with an additional motor restriction which prevented them from using the prohibited finger.

Post-Test. After the intervention, a Post-Test was conducted were both groups again performed the task without motor restriction, identical to the Rule Change block in the beginning.

Transfer Test. In the last two blocks performance on the same task was examined but with two alternated texts. First, a Transfer Test tested performance on a comparable but different text *(transfer text 1).* The rule change remained active.

Specificity Check. Finally, a specificity check was conducted. That is to say, participants had to type a text that did not involve the letters R, F, V, T, G and B, which are normally typed by the left index finger, but which was still comparable in length to the previous paragraphs (*transfer text 2*) (see notions on zero transfer in e.g., Edwards, 2011).

There was a break of one minute after Baseline, Rule Change and Intervention Phase. After completing the typing tasks, the participants responded to an exit online questionnaire of approximately ten minutes. The whole experiment lasted about 45 to 60 minutes.

DATA ANALYSIS

As dependent variables we assessed the *total time* needed for one block, since this global measure comprises both reaction time for each single key press and errors (as errors resulted in increases in total time). In addition, we computed the *Interkeystroke Interval* (*IKSI*; see e.g., Snyder et al., 2015) as a local measure of interference that determines the reaction times for a single key press for keys which were directly affected by the rule change (letters R, F, V, T, G and B). Typing errors also resulted in increased IKSI.

Data Analysis involved three steps. First, a manipulation check was conducted for which we computed two repeated-measures ANOVAs: A 2 (group: VI vs. AMR) x 2 (block: Baseline vs. Rule Change) ANOVA on total time to investigate the change from Baseline to Rule Change and a 2 (group: VI vs. AMR) x 2 (block: Transfer vs. Specificity Check) ANOVA on total time to investigate the specificity of the performance decrements to the affected finger.

Second, to test the effect of the practice interventions, we computed repeated-measures 2 (group: VI vs. AMR) x 3 (block: Rule Change vs. Post vs. Transfer) ANOVAs on both total time and IKSI.

Third, to examine the immediate effects of the verbal instruction and motor restriction, we computed another repeated-measures 2 (group: VI vs. AMR) x 3 (block: Baseline vs. Rule Change vs. first practice block) ANOVA on total time and IKSI.

If the sphericity assumption (Mauchly) was violated, computations were Greenhouse-Geisser corrected. The alpha-level was set at .05 for all statistical tests. If appropriate, significant effects were followed up by Bonferroni-corrected post-hoc t-tests (note that original *p*-values are reported). Effect sizes were calculated using partial eta squared values (η_p^2) or Cohen's *d* for pairwise comparisons (Lakens, 2013).

4.3 RESULTS

MANIPULATION CHECK

The 2 (group: VI vs. AMR) x 2 (block: Baseline vs. Rule Change) ANOVA on total time revealed a main effect for block, $F(1,20) = 163.294$, $p < .001$, $\eta_p^2 = .891$, indicating a significant increase in total time from Baseline to Rule Change (see also Figure 4-2). There was neither a significant main effect for group, $F(1,20) = 2.037$, $p = .169$, $\eta_p^2 = .092$, nor a significant interaction between block and group, $F(1,20) = 2.929$, $p = .102$, $\eta_p^2 = .128$.

Moreover, the 2 (group: VI vs. AMR) x 2 (block: Transfer vs. Specificity Check) ANOVA taking into account the specificity check (which did not require any of the keystrokes affected by the rule change) revealed a significant main effect of block, $F(1,20) = 46.699$, $p < .001$, $\eta_p^2 = .700$, indicating that total time significantly decreased when letters which were directly affected by the rule change were eliminated. There was neither a main effect for group, $F(1,20) = .220$, $p = .644$, $\eta_p^2 = .011$, nor a significant interaction of block and group, $F(1,20) = .952$, $p = .341$, $\eta_p^2 = .045$.

EFFECT OF INTERVENTION

The 2 (group: VI vs. AMR) x 3 (block: Rule Change vs. Post vs. Transfer) ANOVA on total time revealed a main effect for block, $F(1.343, 26.867) = 102.323$, $p < .001$, $\eta_p^2 = .836$, but no main effect for group, $F(1, 20) = .973$, $p = .336$, $\eta_p^2 = .046$. The main effect for block was overruled by a significant block x group interaction, $F(1.343, 26.867) = 4.409$, $p = .035$, $\eta_p^2 = .181$. Post-hoc t-tests revealed no group differences in any of the three blocks (see Table 4-1). As illustrated in Figure 4-2 and indicated by the post-hoc tests (see Table 4-1), regarding total time, both groups significantly improved from Rule Change to Post and Rule Change to Transfer (all $p < .001$), yet only the VI group improved significantly from Post to Transfer.

Table 4-1. Pairwise post-hoc comparisons regarding total time comparing groups (AMR and VI) and blocks (Rule Change, Post, Transfer). Note that the adjusted α-level administering all possible post-hoc t-tests (nine comparisons) is α = .006 (Bonferroni-correction).

Post-hoc comparison	***t***	***df***	***p***	***d***
Rule Change vs. Post (AMR)	7.295	10	< .001	2.200
Rule Change vs. Transfer (AMR)	7.027	10	< .001	2.119
Post vs. Transfer (AMR)	-3.184	10	.010	-0.960
Rule Change vs. Post (VI)	9.170	10	< .001	2.765
Rule Change vs. Transfer (VI)	6.239	10	< .001	1.881
Post vs. Transfer (VI)	-5.265	10	< .001	-1.587
AMR vs. VI (Rule Change)	-1.626	20	.120	-0.693
AMR vs. VI (Post)	0.118	20	.907	.050
AMR vs. VI (Transfer)	-.775	20	.448	-0.330

A corresponding pattern was found for IKSI, taking into account the keys directly affected by the rule change (see Figure 4-3). The 2 (group: VI vs. AMR) x 3 (block: Rule Change vs. Post vs. Transfer) ANOVA yielded a main effect for block, $F(1.231, 24.617) = 76.024$, $p < .001$, $\eta_p^2 = .792$, and a significant interaction between block and group, $F(1.231, 24.617) = 4.505$, $p = .037$, $\eta_p^2 = .184$. The main effect for group was not significant, $F(1, 20) = .740$, $p = .400$, $\eta_p^2 = .036$. Post-hoc t-tests revealed that there were no group differences in any of the three blocks (see Table 4-2). As indicated by these tests, both groups significantly improved from Rule Change to Post and Rule Change to Transfer (all $p < .001$), yet only the VI group improved significantly from Post to Transfer.

Table 4-2. Pairwise post-hoc comparisons regarding IKSI for affected keys comparing groups (AMR and VI) and block (Rule Change, Post, Transfer). Note that the adjusted α-level administering all possible post-hoc t-tests (nine comparisons) is α = .006 (Bonferroni-correction).

Post-hoc comparison	***t***	***df***	***p***	***d***
Rule Change vs. Post (AMR)	6.189	10	<.001	1.866
Rule Change vs. Transfer (AMR)	7.027	10	<.001	2.119
Post vs. Transfer (AMR)	-2.763	10	.020	-0.833
Rule Change vs. Post (VI)	6.850	10	< .001	2.065
Rule Change vs. Transfer (VI)	6.279	10	< .001	1.893
Post vs. Transfer (VI)	-3.798	10	.003	-1.145
AMR vs. VI (Rule Change)	-1.539	20	.139	-0.656
AMR vs. VI (Post)	0.017	20	.987	.007
AMR vs. VI (Transfer)	-0.383	20	.706	-0.163

SHORT TERM EFFECTS

The 2 (group: VI vs. AMR) x 3 (block: Baseline vs. Rule Change vs. P1) ANOVA on total time determined a main effect of block, $F(1.563, 31.266) = 120.560$, $p < .001$, $\eta_p^2 = .858$, and an interaction of group and block, $F(1.563, 31.266) = 3.958$, $p = .038$, $\eta_p^2 = .165$. The main effect of group slightly failed to attain significance, $F(1, 20) = 4.093$, $p = .057$, $\eta_p^2 = .170$.

As indicated by the post-hoc t-tests (see Table 4-3), there was no significant group difference in any of the three blocks. Moreover, performance in both groups significantly degraded from Baseline to Rule Change and Baseline to P1, but improved from Rule Change to P1 (all $p < .002$).

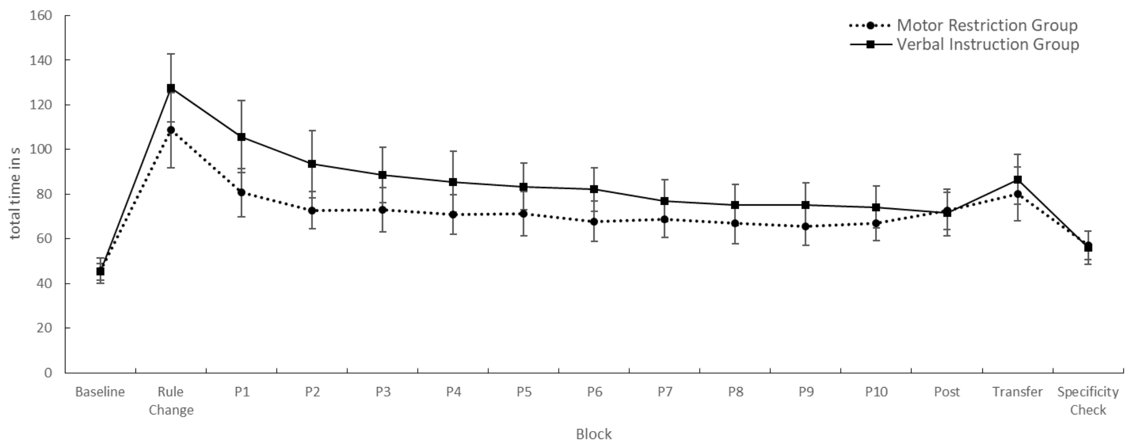

Figure 4-2. Total time in seconds (s) for verbal instruction (VI) group and additional motor restriction (AMR) group over all blocks. P1 to P10 comprises the ten practice blocks in the intervention phase. Error bars indicate 95 % confidence intervals.

Table 4-3. Pairwise post-hoc comparisons regarding total time comparing groups (AMR and VI) and block (Baseline, Rule Change, P1). Note that the adjusted α-level administering all possible post-hoc t-tests (nine comparisons) is α = .006 (Bonferroni-correction).

Post-hoc comparison	***t***	***df***	***p***	***d***
Baseline vs. Rule Change (AMR)	-6.921	10	<.001	-2.087
Baseline vs. P1 (AMR)	-5.501	10	<.001	-1.659
Rule Change vs. P1 (AMR)	5.560	10	<.001	1.676
Baseline vs. Rule Change (VI)	-12.062	10	<.001	-3.637
Baseline vs. P1 (VI)	-48.166	10	<.001	-14.523
Rule Change vs. P1 (VI)	4.727	10	<.001	1.425
AMR vs. VI (Baseline)	.162	20	.873	.069
AMR vs. VI (Rule Change)	-1.626	20	.120	-.693
AMR vs. VI (P1)	-2.550	20	.019	-1.087

Regarding IKSI, the 2 (group: VI vs. AMR) x 3 (block: Baseline vs. Rule Change vs. P1) ANOVA revealed a main effect for block, $F(1.381, 27.626) = 91.717$, $p < .001$, $\eta_p^2 = .821$. However, neither the main effect for group, $F(1, 20) = 3.839$, $p = .064$, $\eta_p^2 = .161$, nor the interaction was significant, $F(1.381, 27.626) = 2.683$, $p = .102$, $\eta_p^2 = .118$.

Pairwise post-hoc tests showed that IKSI for affected keys of all participants regardless of group significantly increased from Baseline to Rule Change and P1 and decreased from Rule Change to P1 (all $p < .001$; see Table 4-4).

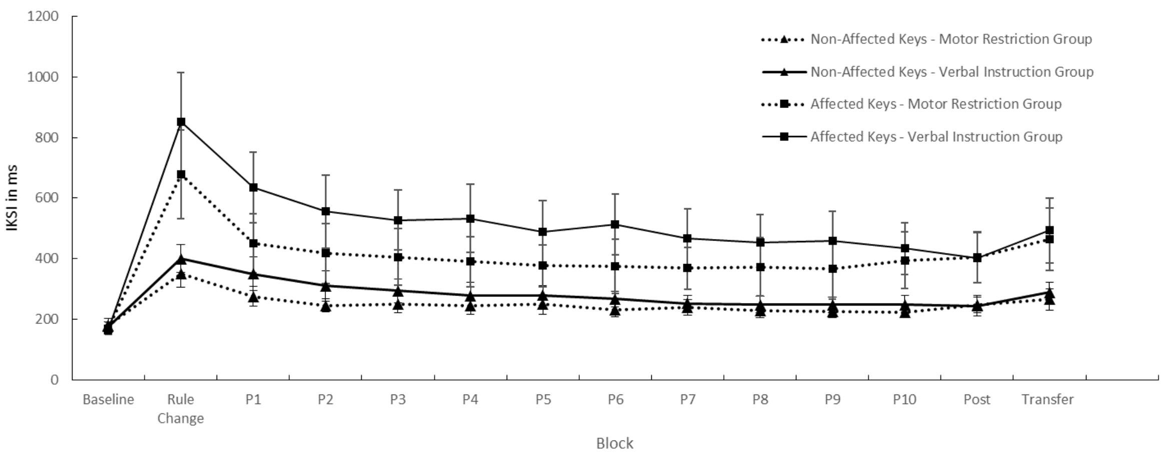

Figure 4-3. IKSI (Interkeystroke Interval) in milliseconds (ms) for rule change affected vs. non affected keys over all blocks for group that received only verbal instruction (VI group) and group with additional motor restriction (AMR group). Error bars indicate 95 % confidence intervals.

Table 4-4. Post-hoc pairwise comparisons regarding IKSI for affected keys comparing blocks (Baseline, Rule Change, P1) over all participants (no group division). Note that the adjusted α-level administering three post-hoc t-tests is α = .017 (Bonferroni-correction).

Post-hoc comparison	***t***	***df***	***p***	***d***
Baseline vs. Rule Change	-10.113	21	< .001	-2.156
Baseline vs. P1	-8.565	21	< .001	-1.826
Rule Change vs. P1	6.908	21	< .001	1.473

EXIT QUESTIONNAIRE

The exit (online) questionnaire revealed two findings that we find worth sharing: First, both intervention groups reported the impulse to still want to use the left index finger for typing in the Rule Change block (VI group: $M = 4.55$, AMR group: $M = 4.09$; note that values ranged from *1 – strongly disagree* to *5 – strongly agree*), during the practice sessions (VI group: $M = 3.64$, AMR group: $M = 2.27$) and in the Transfer Test (VI group: $M = 2.55$, AMR group: $M = 3.09$). As expected, during intervention the impulse was less in the AMR group ($t(20) = -3.141$, $p = .005$). Second, self-rated visual attention changed dramatically from Baseline to the intervention: In the AMR group visual self-rated visual attention towards the monitor dropped from 95 % in the Baseline to 56 % in the Rule Change and during the intervention and 65 % in the Transfer Test. In the VI group self-rated visual attention to the monitor dropped from 93 % in the Baseline to 43 % in Rule Change to 52 % during intervention and 55 % on the Transfer Test.

4.4 DISCUSSION AND CONCLUSION

In this study, we examined whether proactive interference could be reduced by inhibiting the to-be-changed movement pattern by means of a verbal inhibition instruction and an additional physical movement constraint, and whether any of the two interventions may be superior to the other. To start with, initial manipulation checks confirmed that the rule change introduced after the baseline measures produced significant proactive interference effects. That is, when prohibiting the use of the left index finger by means of a rule change, participants' total time increased significantly (see Figure 4-2). The skilled typists needed more than double the time to perform the typing task (despite the fact that the text remained identical). As illustrated in Figure 4-3, this effect was particularly conspicuous for the keys which were directly affected by the rule change (IKSI; keys with the letter R, F, V, T, G or B which are typed with the left index finger by touch-typists). Subjective ratings of participants confirmed pervasive feelings of proactive interference. Participants of both groups reported the impulse to still want to use the left index finger after the rule change, even if this impulse was less in the AMR group during intervention. Interestingly, they also reported that their visual strategies were significantly affected by the rule change. That is, they felt the need to visually control their typing movements on the keyboard and hence reported to spend more time fixating hands and keyboard (and less time on the monitor). Notably, our specificity-check further confirmed that the observed interference was due to the rule change and specific to the letters to-be-typed by the left index finger. More specifically, participants of both groups decreased their total time from the Transfer Test to the Specificity Check block in which the rule was still active but the text did not include letters which were affected by the rule change (i.e., the text did not contain the letters R, F, V, T, G or B).

Concerning the main aims of our study, results showed that the verbal instruction and the additional motor restriction interventions led to significant reductions of proactive interference both immediately following the rule change and after ten practice sessions. This was true for both dependent measures, i.e., total time and IKSI for the affected keys. However, neither of the two interventions was more effective than the other. Or, to put it differently, both interventions were equally effective. More specifically, results revealed that both groups similarly improved from Rule Change to Transfer Test[3] (see Effect of intervention). This supports our conclusion that interventions based on verbal inhibition instructions alone and based on additional motor restrictions were equally effective in reducing proactive interference introduced by the rule change.

What does this result mean on a theoretical level? Based on Chiappe et al. (2000), we argued that verbal instructions are meant to cognitively suppress response tendencies with the aim to inhibit certain behaviours. These verbal inhibition instructions (such as in our experiment "you are no longer allowed to use the left index finger") are likely to require relatively high working memory loads because irrelevant information has to be prevented from accessing working

[3] Please note that, in our view, the most valid assessment of the effectiveness of the interventions results from evaluating the change from Rule Change to Transfer (and not Post). The reason for this is that for the VI group the Post-Test contains actually the same task as in the previous practice blocks (same condition and text), and hence profits a lot from familiarization with the text-specific finger movement sequence. Yet, this is not the case for the AMR group as they practiced with a motor restriction which is now (i.e. in the Post-Test) removed. However, in the Transfer Test both groups are confronted with a new text and which requires a novel finger movement sequences.

memory (*access*) or needs to be suppressed or removed from working memory (*deletion*; (Chiappe et al., 2000). By contrast, concerning the *restraint* function of inhibition (Chiappe et al., 2000), we suggested that a motor restriction (here, the finger bandage) may require less working memory load because it directly eliminates the execution of prepotent response tendencies. In keeping with these assumptions, we predicted that if an additional motor restriction resulted in stronger reductions of proactive interference when changing automatized movement patterns beyond mere cognitive inhibitory processes, this would support the idea that directly addressing the *restraint* function may be crucial to inhibit processes involved in changing automatized movement patterns. However, our results seem to demonstrate that the verbal instructions were equally effective as the additional motor restriction, lending support for an alternative explanation regarding the mechanisms. That is, it seems that the reduction of proactive interference in the motor task applied in this study could be achieved by verbal inhibition instructions alone and hence by mere cognitive inhibition processes including *access* and/or *deletion* (Chiappe et al., 2000). However, these results should be interpreted with caution. The fact that both groups experienced a high amount of proactive interference, but at the same time were able to reduce the experienced interference quite immediately (see strong decline of total time from Rule Change to P1 in both groups) and then continued to only minimally further reduce interference may hint at a ceiling effect. It may be that the amount of proactive interference and its reduction depends on the task. Future research is necessary to test this assumption.

Taken together, these findings raise a number of interesting questions for future research. First, in classical, serial information processing models (for an overview, see Schmidt & Lee, 2011), stimulus identification and response selection precede response programming and movement execution. If, as our results seem to indicate, the motor restriction addressing the *restraint* function does not add to verbal instructions in reducing proactive interference, then this raises the question when inhibition occurs in the process of changing automatized movement patterns. In other words, does inhibition – (even) in motor tasks – occur in earlier cognitive stages rather than in later motor stages? Our initial findings may be interpreted to speak in favour of an early cognitive inhibition through *access* or *deletion* (Chiappe et al., 2000). However, we like to stress that this study did not set out to examine this particular research question, and this is highly speculative and awaits rigorous empirical testing. Nonetheless, if true, one interesting prediction for future research to scrutinize would be that individual differences in (cognitive) inhibition (or, more broadly speaking, executive functions, see e.g., (Miyake & Friedman, 2012), might be a predictor for the success in reducing proactive interference when changing automatized movement patterns. Likewise, factors such as individual interference-proneness (May et al., 1999) may possibly predict inhibition costs in the process of change.

An alternative implication for future research stemming from our findings is to examine whether individuals which permanently or temporarily lack cognitive inhibition control may possibly benefit from applying a motor restriction as it yielded to be similarly effective as verbal inhibition instructions alone. Following a rule change in motor task execution requires working memory resources. It follows that if working memory resources may be temporarily required for other purposes than the process of changing an automatized movement pattern (e.g., a dual-task), then the depletion of working memory capacity for the motor change task may be counteracted by using a motor restriction. This notion needs to be examined in future research.

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APPENDIX

APPENDIX 4-A

Text Stimuli used for the typing task:

Main Text: Bei archäologischen Grabungen ist es überaus wichtig, dass eine detaillierte Dokumentation erfolgt. Ufologen vermuten, dass die Aliens längst hier sind, sie werden von der Nasa verborgen. Werbung ist oft trügerisch und ohne wirklichen Inhalt, hat aber Erfolg.

Transfer Text 1: Seepferdchen haben große Probleme beim Schwimmen, sie treiben bevorzugt in Strömungen. Wer einen Kuchen plant, braucht Zucker und fügt Eier hinzu, Äpfel sind nicht erforderlich. Süßigkeiten sind angeblich Gift für die Figur, der Verzicht fällt trotzdem schwer.

Transfer Text 2: Im Ozean sind die kolossalen Wale kaum zu sehen, doch manchmal kann man ihnen lauschen. Zahllose Menschen hassen Schnee und diese wollen dann ausschließlich zu Hause sein. Dem Klischee nach können Omas ausnahmslos kochen und Kekse und Kuchen schmecken himmlisch.

CHAPTER 5

INTERINDIVIDUAL DIFFERENCES IN THE CAPABILITY TO CHANGE AUTOMATIZED MOVEMENT PATTERNS

STUDY 2

Laura Sperl & Rouwen Cañal-Bruland

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5 INTERINDIVIDUAL DIFFERENCES IN THE CAPABILITY TO CHANGE AUTOMATIZED MOVEMENT PATTERNS

ABSTRACT

When modifying established, automatized skills, performers often experience proactive interference resulting in initial performance decrements. Notably, individuals seem to differ quite largely with respect to their interference susceptibility. The aim of the present study was to scrutinize the roots of these interindividual differences by examining the role of executive functions, age, baseline performance and gaze behavior applying a motor skill change task. As the ability to deal with proactive interference seems to be particularly linked to inhibitory mechanisms, we also assessed whether the application of a motor restriction which prevents unwanted movements may facilitate inhibition and hence result in less proactive interference. To this end, skilled touch-typists were confronted with a rule change that prohibited the left index finger for subsequent typing which immediately disrupted participants' automatized typing fluency. Regression analyses revealed that the amount of interference was significantly related to age and that the application of a motor restriction tended to predict less proactive interference. Additional correlation analyses revealed that a higher amount of proactive interference was also associated with higher baseline performance and lower prepotent response inhibition abilities. However, none of the remaining executive functions could explain the amount of interference. It follows that individual factors such as age, baseline performance and prepotent response inhibition as well as the physical option to execute a certain movement may play important roles in overcoming proactive interference when changing automatized skills.

5.1 INTRODUCTION

The rapid pace of technological advancement combined with the continuous aim to optimize performance pose significant challenges for each individual and demand lifelong learning skills. However, these learning skills do not necessarily require to always acquire completely new skills, but often to adapt or change already existing skills. For instance, when changing from a car with automatic to manual transmission, some components of the general action of driving a car remain identical (such as steering, braking etc.) whereas others change (such as the process of starting, accelerating and stopping which now require to change gears and use the clutch). Usually individuals change and adapt their skills because alternative or new techniques promise better performance, easier execution or other benefits. Counterintuitively though, this change often comes with immediate performance costs. To stick with the car driving example, driving performance may deteriorate when switching from automatic to manual transmission. This decrement is likely to be caused by proactive interference, a forward-directed overlapping of old, existing memory contents with new memory contents (Radvansky, 2017) which occurs especially when two skills (e.g., an old and a new technique) are highly similar, yet not identical. In such situations, as a result of limited memory capacity (Koedijker, Oudejans, & Beek, 2010), stored memory contents and to-be-learned information compete against each other (Edwards, 2011; Tempel & Frings, 2016; Underwood, 1957). This conflict often results in the fact that the pre-existing skill hampers the acquisition or recall of the new, to-be-established skill (Tempel & Frings, 2016).

Consequently, many individuals reflect twice when it comes to the decision whether or not change already existing skills as it (a) requires efforts in terms of time and resources and (b) may be accompanied by initial performance decrements (Carson & Collins, 2016; Oreg, 2003). Moreover, people often prefer to maintain existing habits and are afraid of the risk that the change process may not be successful (Sheth & Stellner, 1979). The main problem with overcoming proactive interference may be that established skills have often become highly automatized and rely on proceduralized knowledge. In other words, for the sake of efficiency, many pre-existing skills run on auto-pilot without extensive reasoning and control. As a consequence, the old, strong and automatized skill competes against the new, not yet established, but relevant skill and proactive interference emerges. This proactive interference in turn then leads to the mentioned performance deterioration (Panzer et al., 2005).

Such as when changing from automatic to manual transmission, changing skills quite often not only encompasses the change of cognitive skills or contents (e.g. memory contents), but involves the modification of motor skills (Carson & Collins, 2015; Kemp & Farrow, 2006; Sperl & Cañal-Bruland, 2020a; Walter & Swinnen, 1994). Yet, despite its commonplaceness and relevance in various contexts such as when adapting to new technology in the workplace, e.g., new technology, dealing with movement constraints, e.g., injuries, or changing a pre-existing technique in sport, e.g., due to rule changes, research on changing automatized motor skill is very limited so far (Sperl & Cañal-Bruland, 2020a). This is even more true for the role of proactive interference in motor skill change (for exceptions, see e.g., Carson & Collins, 2015; Koedijker, Oudejans, & Beek, 2010; Mühlbauer et al., 2007; Mühlbauer & Krug, 2007; Panzer, 2002; Shadmehr et al., 1995).

In keeping with evidence from psychological research on proactive interference, studies examining motor skill change typically report the occurrence of proactive interference when changing from a practiced motor skill towards a similar, yet not identical skill (Koedijker, Oudejans, & Beek, 2010; Mühlbauer & Krug, 2007; Panzer, 2002). However, to the best of our knowledge, none of the aforementioned studies has looked into interindividual differences regarding the amount of proactive interference. This is surprising because research has highlighted that individuals tend to differ with regard to their interference susceptibility (Earles et al., 1997; Hedden & Yoon, 2006; May et al., 1999). It hence seems reasonable to assume that individuals show different amounts of proactive interference resulting in different performance (decrements) when confronted with changing automatized motor skills. If proactive interference indeed varies across individuals, then perhaps the most pressing question to seek an answer to is what the sources of these interindividual differences may be. Answering this question is of utmost important because if factors causing interindividual differences can be pinpointed, then individual solutions (and interventions) can be sought that may help to overcome proactive interference.

As controlling, planning and regulating (motor) behaviour is controlled by executive processes, executive functions are likely candidates to play an essential role when it comes to skill modification. Executive functions are most often divided into three sub-functions: working memory, cognitive flexibility and inhibition (Diamond, 2013; Miyake et al., 2000). As concerns the potential relationship between executive functions and interindividual differences in proactive interference, Hedden and Yoon (2006) found interference susceptibility to be predicted by a series of executive functions, such as shifting between different tasks (i.e., cognitive flexibility), temporarily retaining and processing information in short term or working memory and resisting or suppressing irrelevant memory contents (i.e., inhibition).

In particular, inhibition is known to play a pivotal role in interference control (Earles et al., 1997; Friedman & Miyake, 2004; Levy & Anderson, 2002). Based on original ideas from psychopathological research (Nigg, 2000), Friedman and Miyake (2004) postulate that inhibition involves three sub-dimensions: 1) Resistance to distractor interference refers to the ability to resist interference which emerges from irrelevant information from the external environment (such as distractor stimuli e.g., in the Eriksen Flanker Task; (Eriksen & Eriksen, 1974); 2) resistance to proactive interference denotes the ability to resist internal memory contents regarding information which are now irrelevant but had been previously relevant to the task, e.g., learning novel stimulus-target pairings and being forced to neglect old ones as in AB-AC word lists paradigms (see e.g., Rosen & Engle, 1998); and 3) prepotent response inhibition comprises to the ability to suppress automatic behavioral response tendencies (such as suppressing the automatic tendency to read out a word instead of saying its color in the Stroop Task: (Stroop, 1935). Many inhibition tests (e.g., Erikson Flanker Task, Go/No-Go Paradigms, Word List Learning Paradigms etc.) exist so far and are often used to test "inhibition" in more general terms, while in fact they seem to measure different facets of a multidimensional construct (Friedman & Miyake, 2004). Regarding the pivotal role of inhibitory processes in interference control (Friedman & Miyake, 2004; Levy & Anderson, 2002) the interesting question arises which dimension(s) of inhibition may be able to explain interindividual differences in interference susceptibility. Following our reasoning regarding the central role of proactive interference in skill change, we hypothesize that resistance to proactive interference and prepotent response inhibition are promising candidates to predict performance in skill change tasks. First, if individuals are more resistant to proactive interference, they should be able to resist internal memory contents regarding the pre-existing skill and hence undergo the change process more easily resulting in less performance decrements. Second, prepotent response inhibition as the ability to suppress irrelevant action tendencies may likewise account for the success of a change process, especially in automatized motor tasks.

A closer look at this latter sub-dimension (i.e. prepotent response inhibition) suggests parallels to the restraint function of inhibition which serves the prevention of prepotent responses and action tendencies (Chiappe et al., 2000). In an attempt to address the restraint function of inhibition, Sperl and Cañal-Bruland (2020c) recently used a motor restriction that rendered impossible the execution of unwanted, pre-existing motor processes. The idea was that inhibition might be facilitated when irrelevant movement parts become physically impossible. Like in the present study, the concrete rule change instruction in Sperl and Cañal-Bruland (2020c) prohibited the use of one particular finger during touch-typing. Whereas one group performed this rule change only by following a verbal instruction to not use the respective finger, a second group received an additional motor restriction. More specifically, a finger bandage was applied that rendered any movement of the respective finger impossible. The theoretical reasoning behind this intervention was to address the restraint function of inhibition (see e.g., Chiappe et al., 2000). We reasoned that if it is true that the prevention of prepotent response and action tendencies is an integral component of successful inhibition, then constraining the degrees of freedom by fully withdrawing the motor option of using that finger may foster successful inhibition. By preventing the participants' critical finger from moving towards a key press, the finger bandage is assumed to help resist the temptation to still use that finger and thus may free cognitive resources otherwise spent for controlling prepotent action tendency. In addition, it disables any movement initiation tendencies at the earliest moment possible and may hence save crucial time resources in the elimination and correction of unwanted movements. Having said this, we cannot rule out that (and if so, to what extent) the original motor program is still cognitively evoked. However, following our reasoning, reducing prepotent response tendencies may at least in part facilitate the process of inhibition (see also Sperl & Cañal-Bruland, 2020c).

In addition, using a movement constraint (such as the bandage) over an extended period of time may result in a learning effect. That is, we assume that once the motor restriction is removed the minimized need for inhibition experienced and learned during practice with the constraint may be maintained (i.e. transferred) and result in less proactive interference. The recent study by Sperl and Cañal-Bruland (2020c) did not find that applying a motor restriction over a training session of ten practice blocks was more effective than verbal prohibition instructions alone. However, given that this study only examined relatively short-term learning (i.e. acquisition), more research is necessary to examine to the long-term effects of applying motor restrictions on reducing proactive interference and how the potential benefits may differ interindividually and depend on executive functions.

Taken together, the aim of this study was to examine the nature of interindividual differences in the amount of proactive interference in motor skill change and whether constraining unwanted action options may be beneficial in overcoming this interference. To this end, we applied an experimental paradigm which involved a motor skill change task (identical to Sperl & Cañal-Bruland, 2020c). To experimentally induce proactive interference, we confronted skilled touch-typists with a rule change which disrupted their highly automatized motor skill (that is, touch-typing a text on a computer keyboard). Their individual performance level was first assessed in a baseline test where they had to type a short text as fast and accurately as possible. By then instructing them to not further use the left index finger, but to still type as fast and accurately as possible, we aimed at inducing proactive interference in terms of a performance deterioration (measured as typing time and errors). Applying this task enabled us to assess a motor skill which typically runs highly automatized and for which we could precisely quantify performance. To additionally test whether the effects of proactive interference are not only observable in typing performance, but affect visual attention as well, we also assessed gaze behavior. A characteristic of skilled touch-typists is that they typically need very little visual control of finger movement and key positions as their typing skill is highly automatized (Delleman & Berndsen, 2002). Tracking gaze behavior allowed us to test whether proactive interference may also impact visual strategies. Next to gaze behaviors, baseline performance and age were taken into account when analyzing interindividual differences.

Most importantly, by assessing executive functions we scrutinized whether higher scores in cognitive flexibility, working memory and inhibitory functions may account for the amount of proactive interference in the motor task. We hypothesized that especially individuals with higher resistance to proactive interference and prepotent response inhibition should suffer less from proactive interference and hence perform better after the rule change. To further scrutinize the potential benefit of a motor restriction, we created an additional group which performed the rule change not only following a verbal instruction but with a finger bandage which rendered the use of the left index finger impossible. If inhibition is occurring at least partly on a motor response level, applying a movement constraint and thus withdrawing the option to perform the unwanted movement is predicted to reduce prepotent response tendencies and thus enhance performance after rule change.

5.2 METHODS

PARTICIPANTS

30 skilled touch-typists (11 male; mean age: 31.33, *SD* = 12.46) participated in the experiment. Mean typing speed was 348 characters per minute (CPM; range: 160 – 478), on average they had experience with touch-typing for 15.00 years (*SD* = 11.955). All participants were native speakers (German) who typed regularly in their professional life on computer keyboards (mean typing frequency 4.2 on a scale from 1 never to 5 always). Most of them were members of a stenography and touch-typing association, vocational students or affiliates of the Friedrich Schiller University Jena. The experiment was approved by the Ethics committee of the Faculty of Social and Behavioural Sciences of the Friedrich Schiller University Jena.

MATERIALS

Hardware

The experiment was conducted on a desktop computer (Fujitsu Celsius M740) with an external monitor (Fujitsu P24W-7, size: 24 inch) and standard German QWERTZ keyboard. To collect gaze data a mobile gaze tracker (SMI ETG-2.6-1648-844) with recording of 120 Hz was used.

Executive Function Tests

To assess working memory, cognitive flexibility, prepotent response inhibition and resistance to proactive interference four different executive function tests were applied.

Digit Span Test. Working memory was assessed using the digit span test from the Wechsler Intelligenz Test (WIE; German version of the Wechsler Adult Intelligence Scale WAIS-III). The test provides 16 distinct spans (length of two until nine digits) for forward recall and 14 spans (from two to eight digits) for backward recall. The participant has to verbally repeat each span and the experimenter records the accuracy of the response. The length of spans increases subsequently (distinct spans; two for each length) until the digit span reaches nine items or until the participant cannot repeat both spans of one length correctly anymore (maximum of 16 trials). The same procedure is then conducted again, but with the instruction to repeat the spans backwards. This backwards task has a maximum of 14 trials.

Brown-Peterson Variant. To examine resistance to proactive interference (PI) we used a slightly adapted version of a word recall paradigm based on Kane and Engle (2000), adjusted for German native speakers. This version contains one stimulus set of three PI build-up lists from the same semantic category (animals) and one PI release list with items from another semantic category (professions). Each list consists of ten items (for the complete lists, see Appendix 5-A). As in the original study, items are taken from the lists of category norms by Battig and Montague (1969). After one practice block items of the first lists are presented one at a time centered on screen (font size: 60, black on white background) at an interval of 2000 ms (1750 ms stimulus presentation and 250 ms interstimulus interval). Participants read each presented word aloud. After the last item, the background turns blue and participants have to perform a rehearsal-prevention task (seeing a letter-number-combination, e.g., F-56, and continue this combination forward counting, i.e., "F-56, G-57, H-58" and so on). After 16 seconds the background turns green and participants are instructed to immediately stop the rehearsal-prevention task and start to recall all items they remember from the previous list. The experimenter records all recalled items as well as intrusions. After another 20 seconds, the background turns into red and signals the participants to stop the recall. A break displays on screen for 15 seconds followed before this procedure is repeated for List 2, 3 and 4. The parameter for proactive interference is typically calculated as proportion of loss from List 1 using the formula $[List_1 – List_X] / List_1$. This procedure reveals a single outcome (i.e., dependent measure) for each of the two proactive interference build-up lists ($PI_{List\ 2}$ and $PI_{List\ 3}$) (Kane & Engle, 2000).

Number-Letter Task. To examine cognitive flexibility, we used the number-letter-task based on Monsell (2003), retrieved from the free online platform www.psytoolkit.org. In this test, participants see a 2x2 square of four quadrants in which letter-number-combinations appear. Participants have to perform a reaction task by following two simultaneous task instructions which change in dependence of in which square the stimulus is presented. This task requires to continuously switch attention to different target elements and decide for the respective adequate responses. Whenever the word-number-combination appears in one of the two upper quadrants, they have to perform the letter task by deciding if the displayed letter is a vowel or consonant by pressing a right or a left key on the keyboard. In contrast, when the word-number-combination appears in one of the lower quadrants, participants are instructed to react with the same keys whether the number is odd (left key) or even (right key). The task is to respond as fast and accurately as possible. Participants typically perform a short familiarization practicing the number and the letter task separately for 32 trials each before performing the main task (here 128 trials, see Miyake et al., 2000). Hence, the task requires to continuously switch attention to different target elements and decide for the respective adequate responses. This test allows the estimation of the individual task-switching costs which are the difference of the mean reaction times to repeat-trials (where the task is the same as in the trial before) from those of the switch-trials (where the task is different to the trial right before).

Stop-Signal Task. The Stop-Signal Task is a well-established tool to measure response inhibition (Logan, 2015). We used the Stop-it software from Open Science Framework provided by Verbruggen et al. (2008). Participants perform a decision task pressing a respective button (right or left) when seeing geometric forms (square vs. circle). Whenever a signal tone appears, participants are instructed to interrupt their current response and not press the response button in this trial. The time between the stimulus and the stop signal (stop signal delay) typically varies beginning with a default value of 250 ms in dependence of the participant's test performance. Whenever inhibition has been successful, the stop signal delay is increased by 50 ms, in contrast, when inhibition has not been successful, this interval is reduced by 50 ms. This adaptive testing allows a reliable estimation of the individual stop signal reaction time (SSRT), an estimate of the covert latency of the stop process (Verbruggen et al., 2008). The SSRT is estimated by calculating the difference of mean reaction time and individual mean stop signal delay (for detailed information see Verbruggen et al., 2008). The shorter the SSRT is, the higher is one's capacity of response inhibition. In the present study, after a practice block of 32 trials, participants perform 3x64 trials. Between the blocks participants are given the opportunity to have a short rest, minimally, they have to pause for 10 seconds.

Typing Task

A software programmed with Python was used to present stimulus sentences and measure typing performance, i.e., total time (total time required to type the entire paragraph), Interkeystroke Interval (IKSI; time from one keystroke to the next one), typing speed (characters typed per minute) and errors (wrongly typed keystrokes). Correctly typed characters were highlighted via a green background. In case of a typing error, the colour of the corresponding characters transformed into red signalling the typist to correct the last entry by pressing the correct key to continue.

Independent of experimental condition, participants had to type a short paragraph of five German sentences (67 words, 448 characters, 20.53 % left index finger keys; see Appendix 5-B). In order to ensure typing flow and promote automatized finger movements, we used real sentences as typing material (A. M. Anderson et al., 2009; Gordon et al., 1994; Parasher et al., 2001). The paragraph consisted of grammatically correct German sentences and included only letters and no special signs apart from dot and comma. Content, however, was irrelevant and unrelated. With the aim to compare performance in both conditions and exclude any influence of stimulus difficulty on typing performance, we applied the same stimulus material in both Baseline and Rule Change block (A. M. Anderson et al., 2009; Gordon et al., 1994; Parasher et al., 2001; Sperl & Cañal-Bruland, 2020c).

To realize the additional motor restriction, a finger bandage (Hailicare) was used to restrict participants' left index finger (see Figure 5-1). This bandage was tied around the wrist and finger and fixated the left index finger and thus constraining any movement options of that finger without affecting the range of motion of any other finger of that hand.

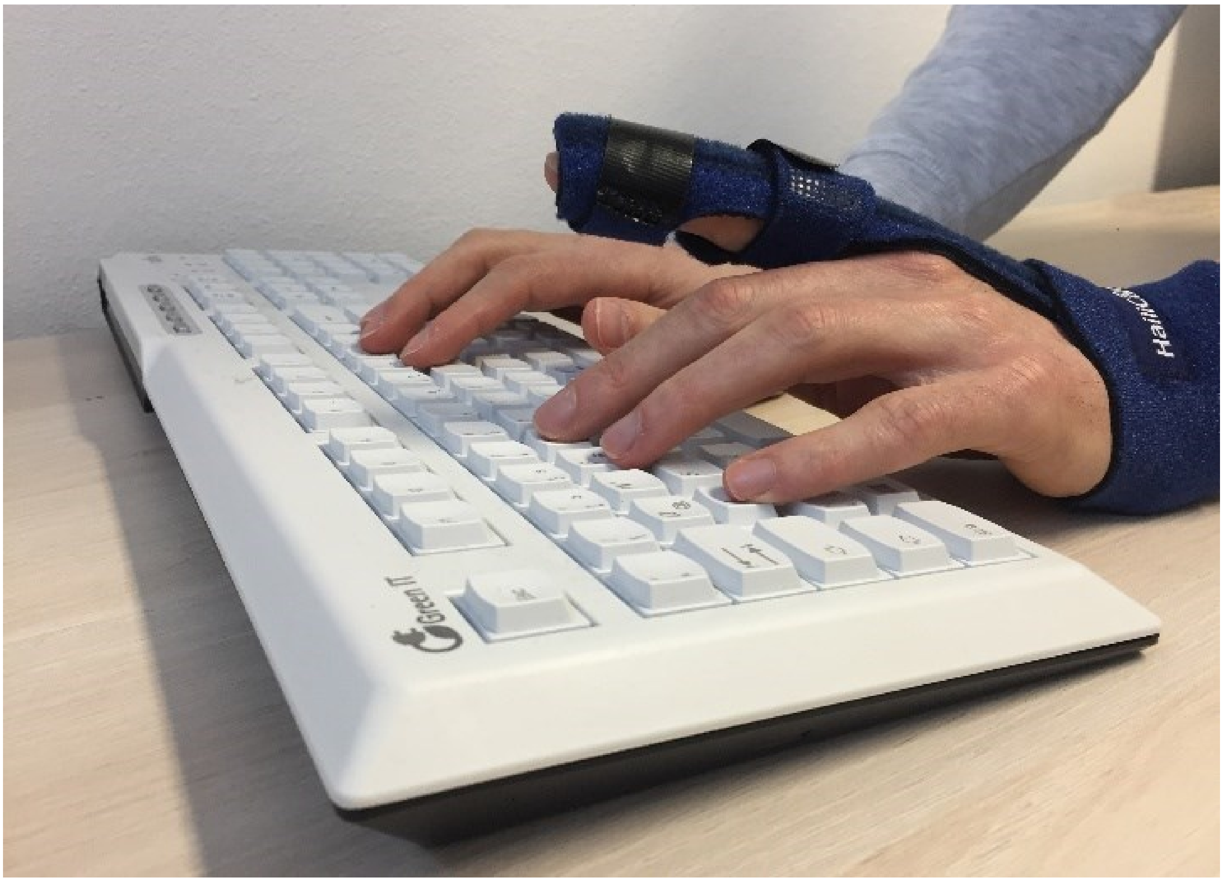

Figure 5-1. Finger bandage used to fixate the left index finger.

Exit Questionnaire

An exit questionnaire, programmed with the online platform Sosci, assessed demographic data as well as past and experiment-related typing experiences.

DESIGN AND PROCEDURE

On arrival at the lab participants provided informed consent and were briefed about the general procedure of the experiment. The experiment then started with the executive function tests in the following order: Digit Span Test, Brown-Peterson Variant, Number-Letter Task, Stop-Signal Task.

After the executive function tests (which took between 30 to 40 minutes), the main part of the experiment started. The experimental paradigm involving the typing tasks were similar to Sperl and Cañal-Bruland (2020c). Participants were randomly assigned to one of two experimental conditions which later received slightly different instructions in the Rule Change (see below). Then, participants were equipped with the portable gaze tracker and a three point-calibration was conducted. Before each task, calibration of the eye-tracking glasses was re-checked. Task instructions were always given in written form before each task. The experiment then started with a short warm-up typing (typing six sentences of prose) to familiarize participants with software, monitor, keyboard and eye-tracking glasses. Participants then performed the two different experimental blocks with the instruction to type as fast and as accurately as possible.

Baseline. In the Baseline block, participants of both groups typed the presented text applying the familiar touch-typing system without any constraint as fast and accurately as possible.

Rule Change. In the next block, the critical rule change was introduced to the participants in order to disrupt the automatized typing behavior. Participants were not allowed to use the left index finger anymore for further typing which according to the touch-typing system affected the key presses of the letters R, F, V, T, G and B. These six letters now had to be pressed by another finger.

Whereas the *verbal instruction* (VI) group only received the verbal instruction to follow this new rule, in the *additional motor restriction* (AMR) group participants' left index finger was fixated with a finger bandage. This motor restriction rendered key strokes with this finger impossible. If in the VI group the left index finger was used despite of the new rule, the experimenter indicated this breach of rule by an auditory signal. Participants of that group were also instructed to avoid abducting the left index finger and leaving it normally on the keyboard.

Finally, the participants responded to the exit questionnaire (ca. five minutes). The whole experiment lasted approximately 60 minutes.

DATA ANALYSIS

The main dependent performance variable for typing performance was the total time needed to type one block, since this global measure comprises both reaction time for each single key press and errors (as errors resulted in increases in total time; see Sperl & Cañal-Bruland, 2020c). One participant had to be excluded from the dataset as it revealed to be an extreme outlier (outmatched the criterion of a maximum of three interquartile distances regarding total time). The amount of experienced interference was calculated as the difference between total time in Rule Change and Baseline. Regarding the performance deterioration from Baseline to Rule Change, also the IKSI for affected vs. non-affected keys was computed and compared.

Gaze data was processed using SMI BeGaze 3.7. A manual event-based semantic gaze mapping was conducted applying gaze information to the three Areas of Interests (AOI): monitor, keyboard and other. Percentaged dwell time for each AOI was computed. Since gaze was mainly directed towards the monitor or keyboard and these two AOIs were widely redundant, we only used percentaged dwell time for keyboard when administering statistical tests. Gaze data of three participants had to be excluded from the dataset due to malfunction in tracking (caused by squinted eyes or eye constitution).

For each executive function test the respective dependent measure reflecting test performance (see Materials) were calculated. For the *Digit Span Test* the dependent measure was simply the amount of correctly repeated spans. For the *Brown-Peterson Variant* the outcome of proactive interference for list 2 and list 3 where used (Kane & Engle, 2000). The ability of prepotent response inhibition is reflected by the SSRT from the *Stop-Signal Task* (Verbruggen et al., 2008). SSRT data of two participants had to be excluded from the dataset because one participant failed to follow the stop instruction at all and another participant's RTs were more than 2 SD from the mean. For the *Number-Letter Task* the task switching costs were used to report performance (Monsell, 2003). Performance variables from the executive function tests were all coded so that higher numeric values stand for better performance in the test.

Statistical analyses involved two main steps. First, a mixed-design 2 (group: VI vs. AMR) x 2 (block: Baseline vs. Rule Change) was conducted for total time and a 2 (group: VI vs. AMR) x 2 (block: Baseline vs. Rule Change) x 2 (key type: affected vs. non-affected keys) for IKSI. Additionally, to scrutinize the visual strategies, another 2 (group: VI vs. AMR) x 2 (block: Baseline vs. Rule Change) was carried out on gaze behavior (percentaged dwell time on keyboard). The alpha-level was set at .05 for all statistical tests. If the sphericity assumption (Mauchly) was violated, computations were Greenhouse-Geisser corrected; effect sizes were calculated as η_p^2.

Second, separate moderated regression analyses were run to investigate the influence of each potential predictor on the strength of interference. This resulted in six separate regressions always including the experimental group plus the respective predictor of interest and their interaction term. These additional predictors were the test performance variables from the executive function tests as well as age and baseline performance (time required to type the presented paragraph). All predictor variables were z-standardized and the experimental group was effect-coded (VI group: -1, AMR group 1). In addition, we tested for correlational relationships between these individual predictor variables (age, baseline, WM span, resistance to proactive interference List 2 and 3, SSRT and cognitive flexibility) and the amount of proactive interference from Baseline to Rule Change computing Pearson correlations.

5.3 RESULTS

TYPING PERFORMANCE

The 2 (condition: VI vs. AMR) x 2 (block: Baseline vs. Rule Change) ANOVA on total time firstly revealed a significant main effect of block ($F(1,27) = 71.66$, $p < .001$, $\eta_p^2 = .73$), indicating that independent of group performance decreased significantly from Baseline to Rule Change, thereby showing that proactive interference was successfully induced. However, there was neither a main effect of condition ($F(1,27) = .196$, $p = .662$, $\eta_p^2 = .01$) nor a significant interaction ($F(1,27) = 2.604$, $p = .118$, $\eta_p^2 = .09$, see Figure 5-2).

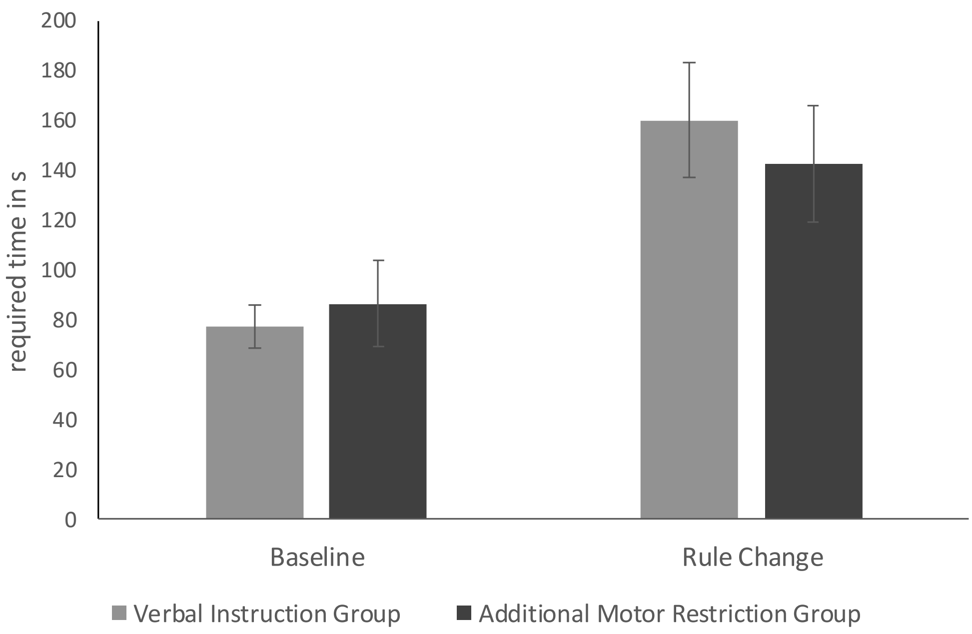

Figure 5-2. Required total time in seconds to type text passage for each block and group. Error bars indicate 95% confidence intervals.

As depicted in Figure 5-3, this effect was particularly conspicuous regarding the keys directly affected by the rule change (R, F, V, T, G and B). A 2 (condition: VI vs. AMR) x 2 (block: Baseline vs. Rule Change) x 2 (key type: affected vs. non-affected keys) ANOVA on IKSI revealed a main effect of block ($F(1,27) = 63.788$, $p < .001$, $\eta_p^2 = .70$) and key type ($F(1,27) = 47.485$, $p < .001$, $\eta_p^2 = .64$) in the absence of a main effect for group ($F(1,27) = .737$, $p = .398$, $\eta_p^2 = .03$).

Moreover, there was a significant interaction between block and key type ($F(1,27) = 42.279$, $p < .001$, $\eta_p^2 = .61$). Neither the interaction between group and block ($F(1,27) = 2.182$, $p = .151$, $\eta_p^2 = .08$) nor the three-way interaction of block*group*key type was statistically significant ($F(1,27) = 1.212$, $p = .281$, $\eta_p^2 = .04$). Figure 5-3 illustrates that participants of both groups needed more than twice the time for the respective key presses (193 ms in Baseline vs. 535 ms in Rule Change) and that this increase in IKSI was particularly strong for the keys which were directly affected by the rule change.

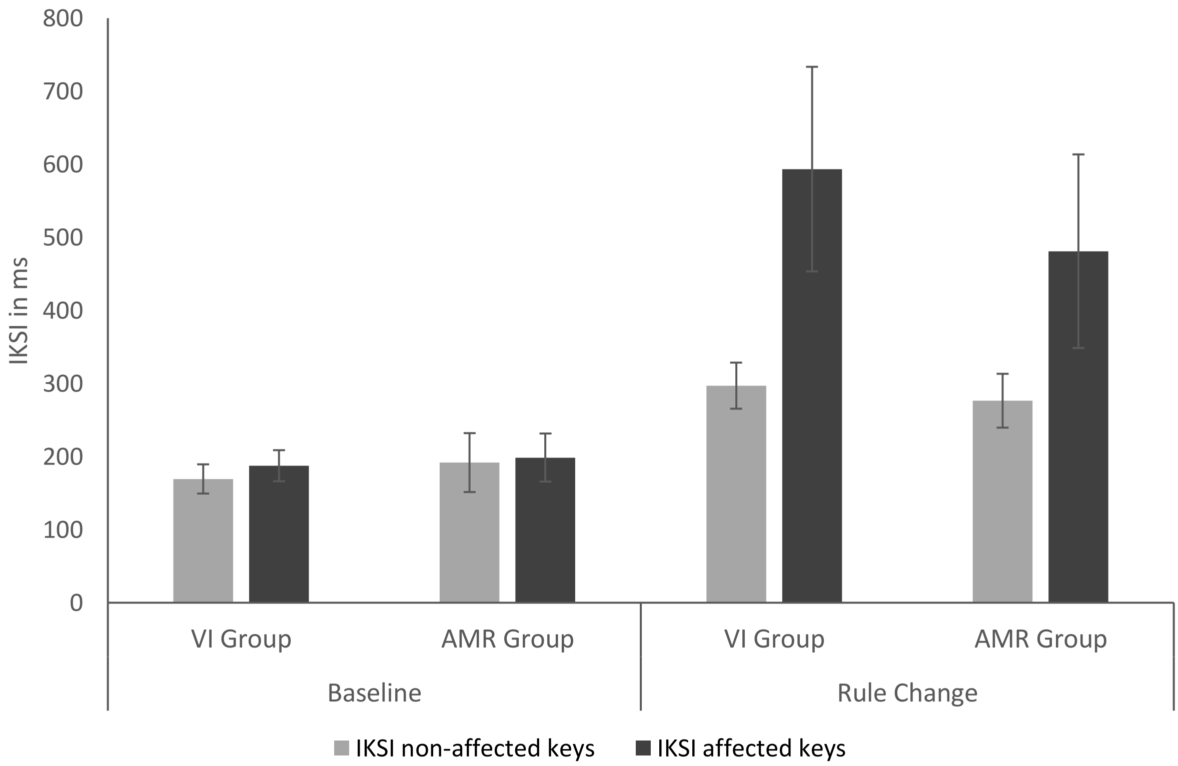

Figure 5-3. IKSI in milliseconds for non-affected vs. affected keys for each block and group. Error bars indicate 95 % confidence intervals.

GAZE BEHAVIOR

Regarding gaze behavior, the 2 (condition: VI vs. AMR) x 2 (block: Baseline vs. Rule Change) ANOVA on percentaged dwell time on keyboard revealed a significant main effect of block ($F(1,24) = 34.083$, $p < .001$, $\eta_p^2 = .59$), no main effect of group ($F(1,24) = 2.615$, $p = .119$, $\eta_p^2 = .10$) and no interaction between these factors ($F(1,24) = .304$, $p = .587$, $\eta_p^2 = .01$). These results show that regardless of the group gaze significantly shifted from the monitor to the keyboard after the introduction of the rule change (for descriptive data, see Table 5-1).

Table 5-1. Percentaged dwell time for monitor and keyboard in Baseline and Rule Change for both VI and AMR Group.

	Baseline				Rule Change			
	Monitor		Keyboard		Monitor		Keyboard	
	M (%)	*SD* (%)	*M* (%)	*SD* (%)	*M* (%)	*SD* (%)	*M* (%)	*SD* (%)
VI	96	5.7	2	4.5	77	17.2	15	14.8
AMR	88	18.6	8	14.1	68	20.0	23	16.7

REGRESSION ANALYSES

Table 5-2 illustrates the data from the separate moderated regressions including each predictor, experimental group, their respective interaction term and the intercept. These regressions revealed that only prepotent response inhibition ($\beta = -.39$, $p = .035$) and age ($\beta = .71$, $p < .001$) significantly predicted the amount of interference. In the regression including age also the experimental group was a significant predictor (age: $\beta = -.33$, $p = .019$), meaning that the AMR group experienced less interference than the VI group. However, whereas the model including age was highly significant ($p < .001$), the model including prepotent response inhibition slightly failed to attain statistical significance ($p = .060$). Another interesting trend was that better baseline performance was associated with higher interference ($\beta = -.44$, $p = .068$), even if the model fit also slightly failed to attain significance ($p = .071$).

Table 5-2. Separate multiple regressions of amount of interference on Working Memory (WM Span), Resistance to Proactive Interference ($PI_{List\ 2}$/$PI_{List\ 3}$), cognitive flexibility (task switching costs), Prepotent Response Inhibition (SSRT), Baseline Performance and Age.

	Predictor	β	SE β	*t*	*p*
Working Memory	Intercept	.01	0.19	0.059	.954
	WM Span	.17	0.21	0.837	.411
	Group	-.28	0.19	-1.515	.142
	WM Span**Group*	.02	0.21	0.091	.928
	Model: $F(3, 25) = 1.089$, $p = .372$, $R^2 = .12$, $R^2_{Adjusted} = .01$				
Resistance to Proactive Interference $PI_{List\ 2}$	Intercept	.03	0.18	0.194	.848
	$PI_{List\ 2}$	.20	0.22	0.921	.366
	Group	-.28	0.18	-1.542	.136
	$PI_{List\ 2}$**Group*	.34	0.22	1.559	.131
	Model: $F(3, 25) = 1.693$, $p = .194$, $R^2 = .17$, $R^2_{Adjusted} = .07$				
Resistance to Proactive Interference $PI_{List\ 3}$	Intercept	.01	0.19	0.051	.960
	$PI_{List\ 3}$	.09	0.19	0.499	.622
	Group	-.29	0.19	-1.556	.132
	$PI_{List\ 3}$**Group*	-.04	0.19	-0.224	.825
	Model: $F(3, 25) = 0.918$, $p = .447$, $R^2 = .10$, $R^2_{Adjusted} = -.01$				
Cognitive Flexibility	Intercept	-.01	0.21	-0.034	.973
	Task Switching	-.04	0.28	-0.152	.881
	Group	-.28	0.21	-1.355	.187
	Task Switching*Group	.05	0.28	0.192	.850
	Model: $F(3, 25) = 0.874$, $p = .468$, $R^2 = .09$, $R^2_{Adjusted} = -.01$				
Prepotent Response Inhibition	Intercept	.01	0.17	0.069	.945
	SSRT	-.39	0.18	-2.237	.035*
	Group	-.33	0.17	-1.872	.074
	SSRT*Group	.02	0.18	0.091	.929
	Model: $F(3, 23) = 2.837$, $p = .060$, $R^2 = .27$, $R^2_{Adjusted} = .17$				
Baseline Performance	Intercept	.006	0.18	0.034	.973
	Baseline	.44	0.23	1.907	.068
	Group	.21	0.18	1.196	.243
	Baseline*Group	-.07	0.23	-0.316	.755
	Model: $F(3, 25) = 2.645$, $p = .071$, $R^2 = .24$, $R^2_{Adjusted} = .15$				
Age	Intercept	.002	0.13	0.019	.985
	Age	.71	0.14	5.166	< .001***
	Group	-.33	0.13	-2.501	.019*
	Age*Group	.18	0.14	1.279	.213
	Model: $F(3, 25) = 10.560$, $p < .001$, $R^2 = .56$, $R^2_{Adjusted} = .51$				

Note: * $p < .05$, ** $p < .01$, *** $p < .001$

CORRELATIONS

Figure 5-4 shows the correlational relationships between the individual predictor variables (age, baseline, WM span, resistance to proactive interference List 2 and 3, SSRT and cognitive flexibility) and the amount of proactive interference from Baseline to Rule Change. Significant correlations were present for age (r = .65, p < .001), indicating that the older the participants the more interference arose, and baseline performance (r = .44, p = .018), indicating that better baseline performance was associated with more proactive interference after rule change. Moreover, there was a significant correlation between SSRT and amount of interference (r = -.40, p = .04), suggesting that a higher ability to inhibit prepotent responses is related to less proactive interference in the experimental task.[4]

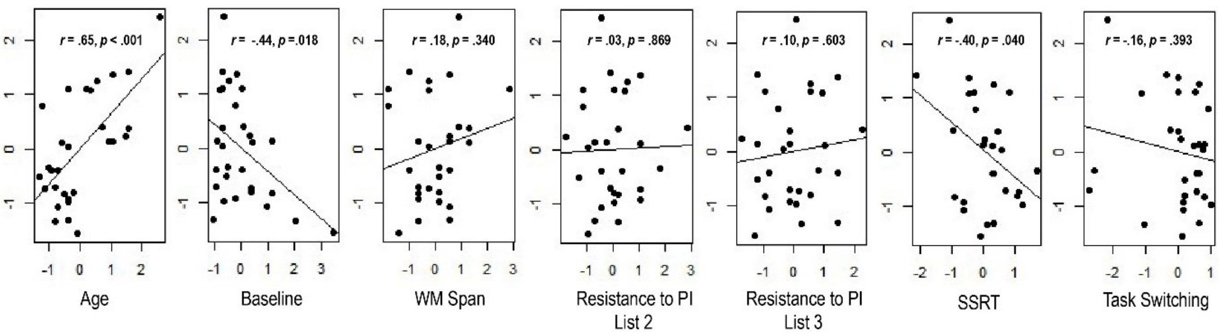

Figure 5-4. Correlation plots for all predictor variables (x-axis; regarding the executive function tests higher scores stand for better performance) with amount of interference (y-axis; higher scores indicate more interference, i.e. higher difference in total time from Baseline to Rule Change). Correlation coefficients and corresponding p-values are depicted.

[4] Note that in this study, SSRT was calculated using the mean method according to Verbruggen et al. (2008). However, there are alternative methods such as e.g. the integration method to compute SSRT (e.g., Matzke et al. , 2018; Verbruggen et al., 2013; Verbruggen et al., 2019). The mean method is known for overestimating SSRT especially if the reaction time distribution is skewed. The integration method, on the other hand, is less sensitive to skewed RT distributions, but tends to underestimate SSRT (Matzke et al., 2018). Since our RT data was not skewed (skewness = 0.56, SE = 0.45), we opted for the classic mean method. Note, however, that if we had applied the integration method, the correlation of SSRT and interference would slightly fail to attain significance (r = -.32, p = .100). The same applies for the regression analyses (SSRT: β = -.26, p = .213; Model: $F(3, 23)$ = 2.288, p = .105, R^2 = .23, $R^2_{Adjusted}$ = .13). We therefore interpreted the significant effect based on the mean method very cautiously.

5.4 DISCUSSION

When modifying automatized movement skills, performers often experience proactive interference resulting in initial performance decrements (Krause, 2017; Panzer et al., 2005). It has been shown that individuals differ quite largely with respect to their interference susceptibility (Earles et al., 1997; Hedden & Yoon, 2006; May et al., 1999). This study aimed at scrutinizing the roots of these interindividual differences by examining the role of executive functions, age, baseline performance and gaze behavior in a motor skill (i.e. touch-typing) change task (Sperl & Cañal-Bruland, 2020c). Because proactive interference is likely to be linked to inhibitory mechanisms (Earles et al., 1997; Friedman & Miyake, 2004; Levy & Anderson, 2002), we additionally assessed whether the application of a motor restriction (i.e. a finger bandage) which prevents unwanted movements may facilitate the process of inhibition in this task and hence result in less proactive interference.

To start with, our results confirmed that the rule change was able to produce significant proactive interference effects: When prohibiting the use of the left index finger (rule change), participants' total time increased significantly (see Figure 5-2). Independent of group the skilled typists needed almost twice the time to perform the typing task (despite the fact that the text remained identical). This effect was particularly conspicuous for the keys which were directly affected by the rule change (IKSI; keys with the letter R, F, V, T, G or B which are typed with the left index finger by touch-typists, see also Figure 5-3). However, also the keys which were not directly affected by the rule change revealed higher IKSI in the Rule Change suggesting some general slowing due to monitoring processes or slowing of neighboring keystrokes (see also Gordon et al., 1994; Jordan, 1995; Snyder & Logan, 2013; Yamaguchi & Logan, 2014).

Results concerning the analysis of changes in gaze behaviors indicated that in both groups gaze shifted from the monitor to the keyboard after the introduction of the rule change. In the baseline condition the touch-typists needed little visual control of their finger movement and/or position of the keys, with average dwell times of 92 % directed at the monitor and only 5 % at hands and keyboard. After the rule change, these values changed to 73 % (average dwell times) gazing at the monitor and 18 % at hands and keyboard (see also Table 5-1). This significant change reveals that the skilled touch-typists needed to visually control their movement executions more after the rule change, thereby indicating that proactive interference is associated with changes in automatized gaze behaviors.

Regarding the interindividual differences, four variables were associated with the amount of proactive interference, that is (i) prepotent response inhibition, (ii) group (verbal vs. motor restriction), (iii) age and (iv) baseline performance.

First, regarding prepotent response inhibition our results showed that better scores in prepotent response inhibition were associated with less proactive interference. Please note that the significance of this finding varies slightly dependent on the method to calculate SSRT, and hence this correlation should be interpreted with caution (see Footnote 1). None of the other executive functions (including cognitive flexibility, working memory and resistance to proactive interference) predicted the amount of proactive interference in our motor change task. On the one hand, this underlines the role of inhibition, and in particular prepotent response inhibition, in overcoming proactive interference (Levy & Anderson, 2002). On the other hand, this finding supports the idea of inhibition representing a multidimensional construct (Friedman & Miyake, 2004). In fact, we tested two sub-dimensions of inhibition, namely prepotent response inhibition and resistance to proactive interference using two different tests. Results revealed that test performance in the Stop-Signal Task (measuring prepotent response inhibition) was associated with the amount of interference whereas performance in the Brown-Peterson Variant (assessing resistance to proactive interference) was not. This may indicate that – at least in motor change tasks – the ability to inhibit prepotent action tendencies seems to be more important than being resistant to intruding memory contents. In planning and executing the to-be-changed action, this could mean that inhibition may occur rather late (closer to the execution process) than early (closer to the cognitive planning), or with regard to the functions of inhibition, address predominantly the restraint function (see also Chiappe et al., 2000). If this reasoning is sound, then we would need to conclude that individuals' prepotent response inhibition capability predicts the costs (i.e. the amount of proactive interference) in motor skill change tasks whereas resistance to proactive interference does not. However, it should be kept in mind that the tests used to assess the different sub-dimensions of inhibition also pose quite different task demands. Whereas the resistance to proactive interference test consisted of a word learning paradigm which requires oral responses and addresses mainly declarative memory, the prepotent response inhibition test requires participants to suppress certain keystrokes when hearing an auditory signal and targets more procedural memory. Given these differences, it may be argued that the touch-typing task resembles more similarities to the Stop-Stop-Signal Task than the Brown-Petersen Variant.

Second, the regression model including age provided initial evidence that the motor restriction led to less proactive interference than the verbal instructions only. This finding may be taken to indicate that the restriction might indeed have helped to suppress unwanted motor tendencies and thus served as an inhibition support. By preventing the participants' left index finger from moving towards a key press, the finger bandage seems to have helped to resist the temptation to still use that finger and may have freed cognitive resources otherwise spent for controlling this finger movement. In more general terms, this seems to suggest that obeying the rule change may be facilitated by withdrawing irrelevant movement options, thereby further supporting the role of prepotent response tendencies in motor skill change tasks. Suppressing strong action tendencies, may it be through inhibitory processes (prepotent response inhibition; cf. the restraint function, Chiappe et al., 2000) or by an additional external restriction, appears to facilitate successful skill modification by reducing proactive interference.

Third, the amount of interference was strongly predicted by age, indicating that the older the participants, the more proactive interference in terms of higher performance deterioration after rule change was observed. This is in line with several studies reporting an increase in the susceptibility to interference with higher age (Bowles & Salthouse, 2003; Earles et al., 1997; Fernandes & Grady, 2008). In addition, our data showed that prepotent response inhibition was significantly correlated with age (r = -.480, p = .011) which converges well with reported inhibition deficits in the elderly (Adólfsdóttir et al., 2017; Hasher et al., 1991). For instance, Rey-Mermet et al. (2018), recently reported significant inhibition deficits explicitly for prepotent response inhibition (but not distractor inhibition) in the elderly population. Also Kramer et al. (1994) found difficulties in older adults to stop overt responses and apply new rules compared to younger participants, whereas other inhibition dimensions were unaffected by increasing age. Despite not being the main focus of our study, our results seem to be in line with these findings, thereby making a contribution to the broader literature on executive functions across the lifespan (Zelazo et al., 2004).

Finally, baseline performance was correlated with the amount of proactive interference, indicating that better touch-typists experienced more proactive interference when confronted with the rule change. On the one hand, this observation is in contrast with theoretical views proposing that skilled performance is amongst others characterized by the ability to flexibly adapt to changed conditions (Ericsson, 2008; Gentile, 1972; for empirical evidence regarding response inhibition, see also Cohen & Poldrack, 2008). On the other hand, however, this finding is well in line with theories of motor learning (Fitts & Posner, 1967) arguing that skilled performance is highly automatized, and that this automatization is beneficial to movement execution under regular conditions but detrimental under changed conditions that may require explicit control, thereby rendering the emergence of proactive interference more likely. It should be noted that we cannot rule out that this relationship between baseline performance and the extent of proactive interference may at least in part be influenced by regression to the mean. Also, in the current study no specific measures were taken to assess the level of automatization. The decision to use skilled touch-typists as participants was fueled by the intention to investigate an already existing and automatized motor skill which seems to be a common procedure in related research (Logan, 2018). Nevertheless, we recommend that future research should include additional measures to be able to quantify the degree of skill automatization of baseline performance.

Another interesting issue for future research is to additionally investigate to which extent processes of deproceduralization (Beilock & Carr, 2001; Ford et al., 2005) might at least in part account for the performance decrements. It is conceivable that the rule change requires a considerable amount of attentional control while the pre-existent automatized skill strongly relies on proceduralized knowledge. This could also result in the case that well learned automatisms that could at least in part be used to solve the new tasks are overruled or inhibited by explicit cognitive control processes due to competition between different memory systems (Poldrack & Packard, 2003). Future research may scrutinize these mechanisms and interindividual differences therein in more detail.

In conclusion, our findings revealed a number of individual factors including prepotent response inhibition, age, baseline performance as well as the physical option to execute a certain movement to play important roles changing automatized movement patterns. In particular, these variables tend to predict the amount of proactive interference experienced in the process of motor skill change on an individual level. Certainly more research is needed to uncover the mechanisms underlying the emergence and reduction of proactive interference in changing automatized movement patterns. This research is required to both improve our theoretical understanding and spark the development of solutions and interventions tailored to the individual that help adapt or change already existing skills to new task demands, may it be in the operating room, at the playing field or in any other context requiring sophisticated motor skills.

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APPENDIX

APPENDIX 5-A

Lists used in the Brown-Peterson Variant.

Practice List	List 1	List 2	List 3	List 4
Baum	Schaf	Giraffe	Ziege	Forscher
Stadt	Eichhörnchen	Wolf	Esel	Polizist
Silber	Leopard	Maultier	Fuchs	Sekretär
Bild	Büffel	Elch	Nashorn	Künstler
Lampe	Antilope	Gazelle	Waschbär	Matrose
Frau	Lama	Stinktier	Gepard	Feuerwehrmann
Garten	Biber	Kojote	Hamster	Präsident
Wille	Streifenhörnchen	Puma	Schildkröte	Friseur
Gurke	Luchs	Affe	Murmeltier	Kraftfahrer
Himmel	Opossum	Krokodil	Hyäne	Musiker

APPENDIX 5-B

Text stimulus used for the typing task:

Wenn Menschen arbeiten, produzieren sie sehr oft etwas. Briefe zu schreiben, bringt heute nur vereinzelt Vorteile, trotzdem muss man nicht darauf verzichten. Viele Menschen üben mehr als nur einen Beruf aus, neben einem sicheren Standbein oft auch etwas Kreatives. Gelegentlich ist man gut damit beraten, sich zu entspannen, auch wenn dieser Zustand nur schwer abrufbar ist. Werbung ist oft betrügerisch und ohne wirklichen Inhalt, hat aber Erfolg.

CHAPTER 6

ON THE ROLE OF DIFFERENT SUBDIMENSIONS OF INHIBITION FOR SUCCESSFUL MOTOR SKILL CHANGE

STUDY 3

Laura Sperl, Thore Gergeleit & Rouwen Cañal-Bruland

SUBMITTED AS

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6 ON THE ROLE OF DIFFERENT SUBDIMENSIONS OF INHIBITION FOR SUCCESSFUL MOTOR SKILL CHANGE

ABSTRACT

Modifying already automatized movement skills often causes proactive interference resulting in initial performance decrements. Dealing with interference is closely linked to inhibitory functions, since inhibition is needed to suppress automatic, but undesired behavior. The aim of this study was to investigate the role of three different inhibition dimensions for interference control in motor skill change. To this end, 42 participants performed three tests each measuring a different dimension of inhibition: *resistance to distractor interfere*nce (Eriksen-Flanker Task), *resistance to proactive interference* (Brown-Peterson Variant) and *prepotent response inhibition* (Stop-Signal Task). To examine the amount of proactive interference in a motor skill change task, participants were then asked to type a short paragraph as fast and accurately as possible on a regular computer keyboard. After this baseline measure, in order to induce proactive interference, they were confronted with a manipulated keyboard on which the letters S and L were switched. This change led to an immediate performance decline, observable in increased typing times and errors. Results also showed that larger performance decrements were significantly associated with better baseline performance, lower scores on prepotent response inhibition and higher scores on resistance to distractor interference. Besides supporting the idea of inhibition as a multidimensional construct, these findings replicate and confirm recent research indicating that the success in motor skill change is predicted by the ability to suppress prepotent response tendencies.

6.1 INTRODUCTION

Have you ever found yourself typing on a foreign computer keyboard and making sporadic, but repeated typing errors? This was probably caused by the fact that a few keys changed in their location. Even if only two letters are switched in their position (as it is the case for, e.g., QWERTZ vs. QWERTY keyboards), it is challenging to suppress the strong and automatic tendencies to strike the keys in their original location and errors continue to occur. Indeed, it is well known that when established automatized motor skills need to be changed, performers often experience immediate performance decrements (Carson & Collins, 2016; Panzer et al., 2005; Sperl & Cañal-Bruland, 2020c). The mechanism causing these decrements is referred to as *proactive interference*.

Proactive interference emerges when old existing memory contents or automatisms compete against the acquisition, execution or recall of a new content (Koedijker, Oudejans, & Beek, 2010; Radvansky, 2017). Interference is particularly strong when two contents or skills are very similar (Underwood, 1957) or when pre-existing skills are highly automatized (Sperl & Cañal-Bruland, 2020a). As a consequence, many people think twice when being confronted with the decision whether to change an already existing skill or accept a suboptimal performance and just stick with it (Oreg, 2003; Sperl & Cañal-Bruland, 2020b). Notably, the extent of experienced proactive interference and the resulting performance decrements vary quite largely across individuals. That is, individuals tend to differ regarding their interference susceptibility (Earles et al., 1997; Hedden & Yoon, 2006) or interference proneness (May et al., 1999).

Traditional proactive interference paradigms usually administer the classic design of comparing an experimental group that first performs a task A and following a rest interval a task B. After a retention interval this group performs task B again. Performance is then compared to a control group that only performed task B in the first period. The extent by which the experimental group performs below the control group on task B is then understood as the amount of proactive interference (M. C. Anderson & Neely, 1996; Schmidt & Lee, 2011; for empirical studies in the motor domain see, e.g., Koedijker, Oudejans, & Beek, 2010; Mühlbauer & Krug, 2007; Shadmehr et al., 1995). This approach allows for high control over the learning process, but depending on the focus of interest may also have important limitations. First and foremost, these paradigms address proactive interference in just-learned skills (often over short periods of time such as single or few experimental sessions) only, and are hence by definition not capable to examine highly automatized procedural skills acquired over longer periods of time, including long-lasting, pre-existing, behavioral patterns often defined as habits (Graybiel, 2008; Linnebank et al., 2018; Walter & Swinnen, 1994). In fact, at least in the motor domain, traditional paradigms sometimes produce initial proactive facilitation instead of proactive interference (Koedijker, Oudejans, & Beek, 2010; Panzer, 2002) and hence do not generate the immediate performance decrements often observed in practice. It follows that in order to investigate proactive interference when highly automatized motor skills are changed requires a different approach.

We recently introduced such an alternative paradigm in a first attempt to scrutinize the roots of these interindividual differences in motor skill change. Specifically, we examined the role of individual factors, such as executive functions, for successful motor skill change (Sperl & Cañal-Bruland, 2020b). Skilled touch-typists with highly automatized typing skills (Logan, 2018) first performed a baseline typing test before the same task was repeated following a new rule. This rule change prohibited the use of the left index finger for subsequent typing, thereby disrupting participants' automatized typing fluency and inducing proactive interference. The amount of interference was measured by quantifying the performance decrements from Baseline to Rule Change. As predicted, results showed that after the rule change performance immediately decreased. Results further revealed that the amount of interference was significantly associated with increasing baseline typing speed and inhibition, more specifically, with the ability to suppress prepotent response tendencies, which was measured by the Stop-Signal Task (Verbruggen et al., 2008). In other words, the higher the prepotent response inhibition abilities were, the less proactive interference was experienced in the typing task, resulting in less severe performance decrements.

Indeed, inhibition is known to play an important role in interference control (Friedman & Miyake, 2004; Levy & Anderson, 2002; Sperl & Cañal-Bruland, 2020b). Often, irrelevant memory contents or undesired action tendencies need to be suppressed to overcome interference and to successfully execute the target task. Nowadays, inhibition is commonly agreed to reflect a multidimensional construct (Diamond, 2013; Kramer et al., 1994; Rey-Mermet et al., 2018; Xie et al., 2017). As a case in point, based on the original ideas by Nigg (2000), Friedman and Miyake (2004) postulate three subdimensions of inhibition: 1) *resistance to distractor interference* referring to the ability to resist interference deriving from irrelevant information (such as distractor stimuli in a reaction time task), 2) *resistance to proactive interference* referring to the ability to resist interference from internal memory contents which are no longer, or currently not, relevant (such as when learning novel stimulus-target pairings in AB-AC word list paradigms) and 3) *prepotent response inhibition* characterized by the ability to suppress automatic response tendencies (such as the automatic tendency to read out a word instead of naming its color in the Stroop paradigm; Stroop, 1935).

As alluded to above, previous research showed that participants' prepotent response inhibition test scores predicted the amount of interference in the typing task, while none of the other assessed executive functions (i.e., task switching, working memory and resistance to proactive interference) did (Sperl & Cañal-Bruland, 2020b). On the one hand, this finding supports the notion of inhibition as a multidimensional construct. On the other hand, it provided initial evidence for a particular role of prepotent response inhibition for successful motor skill change. However, one particular limitation of this research was that while inhibition is typically subdivided into at least three subdimensions (Friedman & Miyake, 2004), Sperl and Cañal-Bruland (2020b) only assessed two of the aforementioned inhibition dimensions, namely prepotent response inhibition and resistance to proactive interference, neglecting resistance to distractor interference. In order to further scrutinize the multidimensional character of inhibition, in the current study, we therefore also included a measure of resistance to distractor interference, thereby covering all three subdimensions.

Another critical issue in Sperl and Cañal-Bruland (2020b) concerns the way proactive interference was induced. As described above, the skilled touch-typists first performed a baseline typing test, followed by a rule change condition in which they were instructed to not use the left index finger for subsequent typing anymore. This was either implemented by verbal instructions alone or verbal instructions supplemented by an additional finger bandage restricting any movements of the left index finger, thereby preventing undesired motor actions. The idea of these two groups was to examine whether the application of a motor restriction that rendered undesired movements (i.e. rule breaching movements) impossible facilitated inhibition and caused less proactive interference (for a more detailed reasoning, see Sperl & Cañal-Bruland, 2020b, 2020c). As illustrated by the introductory example, these manipulations do only cover a subset of situations that demand motor skill changes. That is, when switching, for instance, from a QWERTZ to QWERTY keyboard, this does neither correspond to a pure verbal instruction indicating a rule change nor to a physical constraint, limiting the degrees of freedom (Newell, 1986). It hence remains to be determined whether the findings from Sperl and Cañal-Bruland (2020b) not only apply when physical effectors, limiting the degrees of freedom and hence the chance to exploit individual solutions to master the changed task, are constrained, but also transfer to rule change manipulations which involve equipment changes like in the keyboard example.

Taken together, the aims of the current study were twofold: first, we sought to scrutinize the particular role of inhibition as a predictor for interindividual differences in motor skill change by examining all three subdimensions of inhibition, that is, resistance to distractor interference, resistance to proactive interference and prepotent response inhibition (according to Friedman & Miyake, 2004). Second, we examined whether both proactive interference effects as well as the relation with prepotent response inhibition transfer to situations that are characterized by changes to the equipment rather than by manipulations to physical effectors such as restrictions of limb movements.

To this end, similar to Sperl and Cañal-Bruland (2020c) and Sperl and Cañal-Bruland (2020b), we also applied a typing paradigm since typing constitutes a motor skill which nowadays, even without specific formal training, is usually highly automatized and frequently used among a large part of the population (Logan, 2018). More specifically, after completion of three different inhibition tests, participants were first asked to type a short paragraph as fast and accurately as possible on a regular computer keyboard. Participants were then confronted with a manipulated keyboard on which two letters were switched in their position, referred to as *key switch* condition (Gordon et al., 1994; Jordan, 1995; Parasher et al., 2001; Yamaguchi & Logan, 2014). As dependent measures we assessed total time required to type the whole paragraph, the interkeystroke interval and typing errors, which allowed us to quantify typing performance in detail.

First, based on Sperl and Cañal-Bruland (2020b), we predicted that amount of performance deterioration would be associated with lower prepotent response inhibition scores, but that there would be no association between resistance to proactive interference and the amount of performance decrements. Regarding resistance to distractor interference, we also did not predict an association with proactive interference as no particular distractor stimuli were present in either condition. Thus, by explicitly hypothesizing that one dimension was related to successful motor skill change, whereas the other two were not, we pursued a discriminant approach (see also notions on convergent and discriminant validity, e.g., Vaughn & Daniel, 2012). Finally, we predicted that especially those participants with a high baseline typing speed (whose typing skill is suggested to be highly automatized), would experience more proactive interference, resulting in larger performance decrements (Sperl & Cañal-Bruland, 2020b).

6.2 METHODS

PARTICIPANTS

42 participants[5] (19 females, mean age: 22.6, range: 17 – 30 years) took part in the experiment. Participants' mean typing speed was 35.18 words per minute (WPM; determined via Baseline measure; range: 21 – 59 WPM). On average, participants acquired the typing skill at the age of 10 (range: 6 – 16 years). The experiment was approved by the Ethics committee of the Faculty of Social and Behavioural Sciences of the Friedrich Schiller University Jena (FSV 18/24).

MATERIALS

Hardware

The typing task and the inhibition tests were conducted on a computer (Fujitsu Celsius M740) with an external monitor (Fujitsu P24W-7, size: 24 inch) and standard German QWERTZ keyboard (Fujitsu Green it). For the key switch condition an identical second keyboard was used where the keys of the letters S and L were physically (and digitally) switched.

Inhibition tests

All three tests to measure the different subdimensions of inhibition were selected based on Friedman and Miyake's comprehensive latent-variable analyses on inhibition-related functions (see also Friedman & Miyake, 2004 for details on test parameters and extensive discussion).

[5] Since one of the main aims of this study was to test whether the effect of prepotent response inhibition reported in Sperl and Cañal-Bruland (2020b) replicates and transfers to the present paradigm, we computed an a-priori power analysis based on their effect. This yielded a minimum sample size of 37 participants (based on a correlation of r = -.40 (tested one-sided), power = .80 and α = .05).

Brown-Peterson Variant. A slightly adapted version of a word recall paradigm based on Kane and Engle (2000) was used and adjusted to German native speakers to examine resistance to proactive interference (PI). This version consists of a practice list, three PI build-up lists of ten words each from the same semantic category (animals), and one PI release list containing words from another semantic category (professions) (for the complete lists, see Appendix 5-A). As in Kane and Engle (2000), items are taken from the lists of category norms by Battig and Montague (1969). Items are presented one at a time in the center of the screen (font size: 60, black on white background) at an interval of 2000 ms (1750 ms stimulus presentation and 250 ms interstimulus interval). Participants are instructed to read aloud each presented word. After each list, the background turns blue and participants are instructed to perform a rehearsal-prevention task (seeing a letter-number-combination, e.g., C-15, and continue this combination forward counting, i.e., "C-16, D-17, E-18" and so on) for 16 seconds. In the following recall phase, participants have 20 seconds to recall all words they remember from the previous list until the background turns into red, signaling the participant to stop recall. Recalled words and intrusions are checked by the experimenter. There is a break of 15 seconds between each list. Resistance to proactive interference is calculated as proportion of loss from List 1 following the formula $[List_X – List_1] / List_1$. This procedure reveals two separate outcomes (i.e., dependent measure) for each of the two proactive interference build-up lists ($PI_{List\ 2}$ and $PI_{List\ 3}$) (Kane & Engle, 2000).

Eriksen-Flanker Task. To examine resistance to distractor interference, the Eriksen-Flanker Task (Eriksen & Eriksen, 1974) was executed. In this test, participants are instructed to classify a target letter as fast and as accurately as possible. Whenever the target letter is a V or B, they must press the right key, when the target letter is an X or a C, they must press the left key. In most cases, this target letter is embedded in a row of 4 identical distractor letters (also X, C, V or B). In compatible trials the target calls for the same reaction key as the distractor letter would require (e.g., XXCXX). In incompatible trials the target requires a different response than the distractor letters would demand (e.g., XXVXX). Only in a low amount of trials (eight per block) the target letter is displayed without distractor letters. A fixation cross of 500 ms is displayed in the center of the screen before each trial. Here, the task consisted of a practice block of 32 trials and 4 experimental blocks of 40 trials. The stimuli were displayed in the center of the screen (font size: 40) until a response key was pressed. In order to provide feedback to the participant, feedback was provided in green or red color after each trial. Resistance to distractor interference is calculated through the difference of RT on incompatible and compatible trials. According to the procedure by Friedman and Miyake (2004), any RT values exceeding the range of 200 to 1500 ms were replaced with these upper or lower criterion values.

Stop-Signal Task. To measure prepotent response inhibition, we used the Stop-Signal Task (Logan, 2015) which is provided by Verbruggen et al. (2008) via the Stop-it software and can be accessed on the Open Science Framework (https://osf.io/wuhpv). In this task, participants perform a simple classification task in which they have to press a right button when they see a circle and a left button when they see a square. Participants are instructed to execute this task across all trials, but to immediately interrupt their response whenever a signal tone appears. In this case they are asked not to press any button, that is, inhibit the motor response. In the present study, participants performed 3x64 trials (preceded by a practice block of 32 trials). Furthermore, the test is adaptive and thus varies the time between the stimulus and the stop signal (stop signal delay) in dependence of the participant's test performance beginning with an interval of 250 ms. Whenever inhibition is successful, the stop signal delay is increased by 50 ms, when inhibition fails, it is reduced by 50 ms. This allows a reliable estimation of the covert latency of the stop process (Verbruggen et al., 2008). Here, SSRT is estimated using the integration method (for a detailed description see e.g., Verbruggen et al., 2013). Lower SSRT values reflect higher response inhibition abilities.

Typing Task

A program was coded with Python which allowed to present stimulus sentences, provide feedback and measure typing performance in terms of total time (total time required to type the entire paragraph), interkeystroke interval (IKSI; time from one correct keystroke to the next correct entry), typing speed and errors (wrongly typed keystrokes). In case of false keystrokes, the background color of the respective character turned into red, signaling the participant to correct the last entry by pressing the correct key to continue. All correctly typed characters turned green the moment the correct letter was entered.

In each of the two blocks participants had to type a short paragraph of six sentences (113 words, 742 characters, 45x letter L and 45x letter S, see Appendix 6-A). These sentences were chosen with the aim to provide a considerable and equally-distributed amount of the letters L and S while presenting grammatically correct German sentences. They included only letters and no special signs apart from dot and comma. Semantic content of these sentences was irrelevant and unrelated. We opted to use real sentences for both blocks as typing material in order to promote automatized finger movements and typing flow and exclude any potential influence of stimulus difficulty (for similar procedures, see A. M. Anderson et al., 2009; Gordon et al., 1994, 1994; Parasher et al., 2001; Sperl & Cañal-Bruland, 2020b, 2020c).

Exit Questionnaire

A short exit questionnaire was conducted to asses age, gender, handedness and familiarity with keyboard typing.

DESIGN & PROCEDURE

On arrival at the lab participants provided informed consent and were briefed about the general procedure of the experiment. The experiment started with the inhibition tests in the following order: Stop-Signal Task, Eriksen-Flanker Task and Brown-Peterson Variant. Instructions were always given in written form. Participants then started with the typing task, after a short familiarization with the keyboard and set-up in a brief warm-up phase which consisted of typing a short paragraph of six sentences. Subsequently, participants absolved the two different experimental blocks with the instruction to type as fast and accurately as possible.

Baseline. In the Baseline condition, participants typed the presented paragraph in the habitual manner.

Key Switch. In the Key Switch block, participants were confronted with a keyboard where the letters S and L were switched in their positions. In simple words, this means that they received the changed instruction that whenever they saw the letter L in the text, they now had to press the letter S (now at the original location of L) and vice versa. The letters S and L were chosen for the key switch manipulations as their positions on the QWERTZ keyboard are symmetrical which leads to comparable biomechanical demands of these keystrokes.

In addition, these letters are quite distant from each other and hence are most probably pressed by different fingers (Parasher et al., 2001). Furthermore, they have a similar frequency in German language (www.duden.de/sprachwissen/sprachratgeber/Die-haufigsten-Buchstaben-deutschen-Wortern).

Note that, we opted for keeping the order of these blocks constant as we were interested in assessing proactive interference from a pre-existing skill (which of course was existent already before pre-test session). We, hence, followed the order which also characterizes skill change processes in real life (starting at the habitual skill and then introduce the change). Thereby, the baseline block is intended to function as a pre-test and not (primarily) as a proactive interference build-up manipulation. In order to pose the same biomechanical demands and exclude any influence of stimulus difficulty and thereby be able to compare performance from Baseline and Key switch adequately, also the stimulus text remained identical (see above). Importantly, any potential familiarization or practice effects following this blocked design would diminish our expected effects rather than increasing them.

After each block participants provided a short subjective rating of how they thought they had divided their visual attention between focusing on their fingers (i.e. their typing actions on the keyboard) and the monitor. To this end, they drew a vertical line on a 10 cm long horizontal line with "keyboard/fingers" on the left end and "monitor" on the right end of the scale.

The participants completed the experiment by answering the exit questionnaire.

DATA ANALYSIS

All collected data were digitized and prepared for Data Analysis. Typing performance was measured via total time, IKSI, total errors and errors on critical keys, constituting four different dependent variables. Error parameters were corrected by transforming multiple errors on a single occasion of a certain letter into only one error on that letter entry. Hence, a single keypress was counted as either correct or false in order to avoid overweighting multiple errors on the same key which occurred, for example, when a participant did not notice an error and continued typing the subsequent letters. The amount of proactive interference was calculated as the difference of these typing performance variables between the Key Switch and Baseline condition. All parameters of the inhibition tests were coded so that higher values indicate better performance in the respective test.

The following Data Analysis involved two steps. First, two-tailed paired t-tests were conducted for each typing performance parameter to check for a difference from Baseline to Key Switch and hence test whether the key switch paradigm induced proactive interference. In addition, to compare the change in IKSI for critical compared to non-critical keys, a 2 (block: Baseline vs. Key Switch) x 2 (key type: critical vs. non-critical) ANOVA was performed. In a second step, four multiple regression analyses were conducted for each dependent variable of performance change (including total time, $IKSI_{S/L}$, total errors and $errors_{S/L}$). Within these regression models five predictor variables were entered into the model, that includes Baseline WPM (baseline performance), SSRT (prepotent response inhibition), Flanker effect (resistance to distractor interference) and $PI_{List\ 2}$ and $PI_{List\ 3}$ (resistance to proactive interference). Additional analyses checked for intercorrelations between the inhibition subdimensions. The alpha-level was set to .05 for all statistical analyses. Effect sizes were calculated as Cohen's *d*, correlations as Pearson's *r*.

6.3 RESULTS

AMOUNT OF INTERFERENCE AND CHANGE IN TYPING PERFORMANCE

Paired t-tests revealed that typing performance decreased significantly from Baseline to Key Switch which was observable for all performance parameters (see Table 6-1, for descriptive and inferential statistics). Specifically, after the key switch, participants needed more time to type the same paragraph (mean difference: 84.6 seconds) and produced more errors (mean difference: 9.6). This was also observable on the level of the single key presses and here particularly conspicuous for IKSI on the switched keys ($IKSI_{S/L}$). Whereas the IKSI on non-critical keys increased on average by 55 ms, $IKSI_{S/L}$ increased by 539 ms after the keys were switched (see also Figure 6-1). This pattern was confirmed by a 2 (block: Baseline vs. Key Switch) x 2 (key type: critical vs. non-critical) ANOVA revealing significant main effects for block ($F(1,41) = 582.937$, $p < .001$) and key type ($F(1,41) = 566.705$, $p < .001$) as well as a significant key type by block interaction ($F(1,41) = 508.601$, $p < .001$). In the Baseline 16 % of the errors were made on the keys S and L, in the Key Switch 49 % of the errors made occurred on one of these critical keys. Regarding the $errors_{S/L}$ and $IKSI_{S/L}$ not only the means, but also the standard deviations increased drastically (see Table 6-1 and Figure 6-1), further indicating strong interindividual differences in the amount of interference.

Table 6-1. Descriptive data and inference statistical parameters for typing performance variables.

	$M_{Baseline}$	(SD)	$M_{Key\ Switch}$	(SD)	*t*	df	*p*	*d*
Total time (in s)	202.2	(46.4)	286.8	(43.8)	-22.031	41	< .001	-3.399
$IKSI_{S/L}$ (in ms)	309	(97.8)	848	(154.6)	-23.680	41	< .001	-3.654
$IKSI_{Other}$ (in ms)	268	(59.8)	323	(53.3)	-14.388	41	< .001	-2.220
Total errors	27.4	(14.1)	37.0	(3.0)	-4.513	41	< .001	-0.696
$Errors_{S/L}$	4.3	(3.7)	18.1	(10.7)	-9.254	41	< .001	-1.428

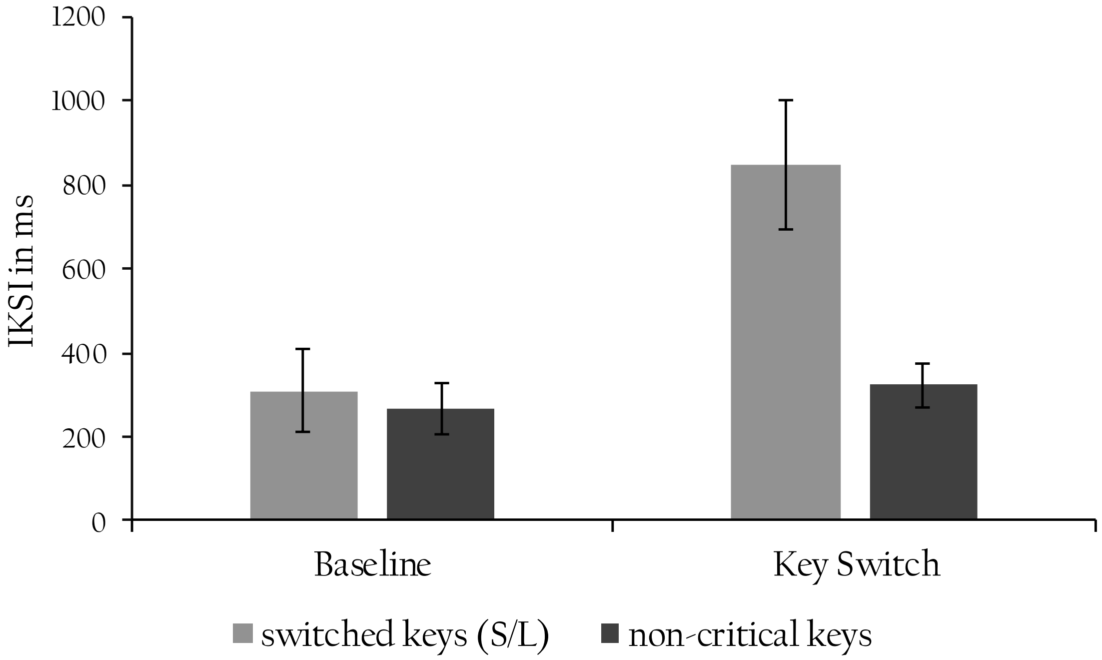


Figure 6-1. IKSI for switched keys ($IKSI_{S/L}$) and non-critical keys ($IKSI_{Other}$) in Baseline and Key Switch condition. Error bars indicate standard deviations.

Moreover, subjective ratings of how visual attention was divided between focusing on the keyboard/fingers and focusing on the monitor revealed that participants self-reported to direct their visual attention significantly more towards their hands and the keyboard after the key switch ($t(41) = 6.795$, $p < .001$, $d = 1.048$).

INTERINDIVIDUAL DIFFERENCES IN THE AMOUNT OF INTERFERENCE

Results of the regression analyses are depicted in Table 6-2, scatterplots of the descriptive data can be inspected in Figure 6-2. The regression analyses revealed three significant predictors. First, baseline typing speed predicted the amount of interference in terms of total time difference, error difference and errors on switched keys (all ps ≤ .016), indicating that a higher baseline typing speed led to more interference. Second, prepotent response inhibition predicted the difference in total errors ($\beta = -.57$, $p < .001$) and errors on switched keys ($\beta = -.44$, $p = .002$). More specifically, as illustrated in Figure 6-2, better prepotent response inhibition abilities were associated with less performance decrements. For total time, also resistance to distractor interference significantly predicted the amount of proactive interference ($\beta = .32$, $p = .039$). That is, better performance in the Eriksen-Flanker Task was related to larger performance decrements after the key switch.

Importantly, and following the notions that these inhibition dimensions represent different subsets of the construct of inhibition, with the exception of prepotent response inhibition and resistance to distractor interference ($r = .31$, $p = .049$), the inhibition measures revealed no significant intercorrelations (all $p \geq .143$).

Table 6-2. Separate multiple regressions of amount of interference on baseline typing speed (Baseline WPM), prepotent response inhibition (SSRT), resistance to distractor interference (Flanker effect) and resistance to proactive interference ($PI_{List\ 2}$/$PI_{List\ 3}$).

Dependent Variable	Predictor	β	SE β	*t*	*p*
	Intercept		26.70	0.288	.775
total time	Baseline WPM	.46	0.45	3.246	.003**
	SSRT	-.18	0.09	-1.204	.236
	Flanker effect	.32	0.11	2.147	.039*
	$PI_{List\ 2}$	-.17	14.37	-1.198	.239
	$PI_{List\ 3}$	-.01	12.77	-0.077	.939
	Model: $F(5, 36) = 3.128$, $p = .019$, $R^2 = .30$, $R^2_{Adjusted} = .21$				
$IKSI_{S/L}$	Intercept		175.86	1.824	.076
	Baseline WPM	.25	2.98	1.612	.116
	SSRT	-.08	0.57	-0.513	.611
	Flanker effect	.16	0.73	0.975	.336
	$PI_{List\ 2}$	-.20	94.65	-1.277	.210
	$PI_{List\ 3}$	.19	84.09	1.163	.252
	Model: $F(5, 36) = 1.156$, $p = .349$, $R^2 = .14$, $R^2_{Adjusted} = .02$				
total errors	Intercept		13.61	-4.155	< .001***
	Baseline WPM	.33	0.23	2.538	.016*
	SSRT	-.57	0.04	-4.221	< .001***
	Flanker effect	.15	0.06	1.067	.293
	$PI_{list\ 2}$	-.18	7.32	-1.392	.173
	$PI_{list\ 3}$	-.01	6.51	-0.092	.928
	Model: $F(5,36) = 5.003$, $p = .001$, $R^2 = .41$, $R^2_{Adjusted} = .33$				
	Intercept		9.27	-3.402	.002**
$errors_{S/L}$	Baseline WPM	.50	0.16	3.979	< .001***
	SSRT	-.44	0.03	-3.385	.002**
	Flanker effect	.14	0.04	1.028	.311
	$PI_{List\ 2}$	-.23	4.99	-1.768	.086
	$PI_{List\ 3}$	.17	4.43	1.320	.195
	Model: $F(5,36) = 5.757$, $p = < .001$, $R^2 = .44$, $R^2_{Adjusted} = .37$				

Note: * $p < .05$, ** $p < .01$, *** $p < .001$

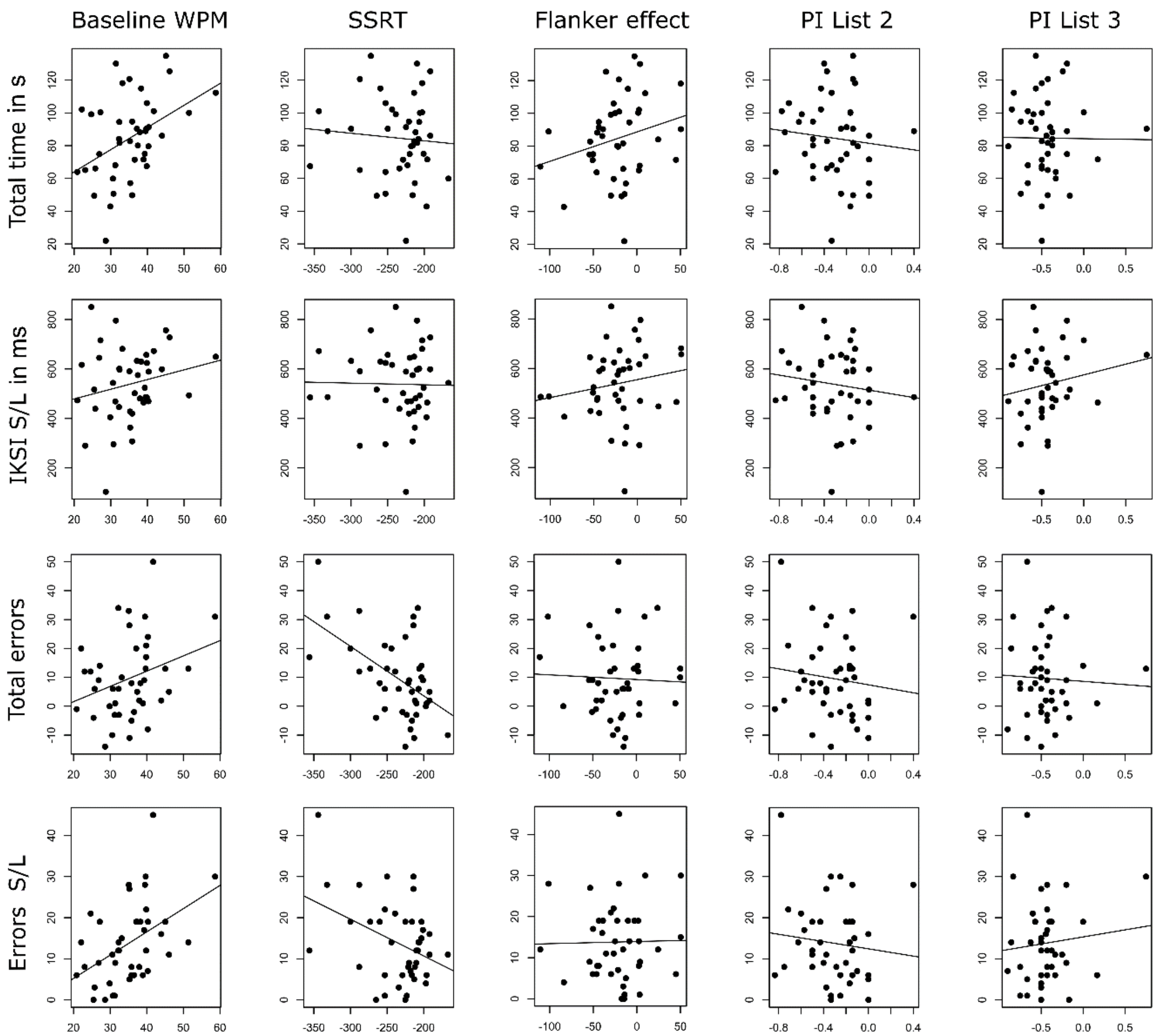


Figure 6-2. Scatterplots for all predictor variables (on the x-axes; for the inhibition tests higher scores indicate better performance). The amount of interference is reflected by increases in total time in s, $IKSI_{S/L}$ in ms, total errors and $errors_{S/L}$ (y-axes; higher scores indicate more interference, i.e. larger differences between Baseline and Key Switch).

6.4 DISCUSSION

When changing existing motor skills, automatisms often lead to proactive interference causing initial decrements in performance (Panzer et al., 2005). The extent of this performance deterioration varies across individuals (Sperl & Cañal-Bruland, 2020b). It is suggested that inhibitory abilities play an important role in interference control (Friedman & Miyake, 2004; Levy & Anderson, 2002). Therefore, the aims of the present study were i) to scrutinize the particular role of inhibition as a predictor for interindividual differences in motor skill change, and ii) to examine whether previously reported effects also generalize to changes to the equipment. To this end, in the present study, participants were confronted with a key switch affecting their regular typing on a computer keyboard. Specifically, after typing in the regular manner in a baseline block, the keys S and L were switched regarding their positions on the keyboard. This manipulation aimed at forcing participants to at least partially change and suppress the existing automatized typing skill to cope and effectively deal with the novel task demands.

Indeed, significant increases in total typing times and errors showed that the key switch manipulation was able to induce proactive interference (Gordon et al., 1994; Jordan, 1995; Parasher et al., 2001; Yamaguchi & Logan, 2014). On average participants' total time to type the identical paragraph increased by 84.6 seconds and typing was more error-prone after the key switch. This effect was particularly conspicuous for the keys which were directly affected by the change. The time required to strike the correct keys almost tripled when a switched letter had to be pressed, typing errors even quadrupled (see also Figure 6-1 and Table 6-1). These results, building up on earlier findings administering similar manipulations (Gordon et al., 1994; Jordan, 1995; Parasher et al., 2001; Sperl & Cañal-Bruland, 2020b, 2020c; Yamaguchi & Logan, 2014) and strongly suggest that performance deterioration was due to the key switch and not caused by statistical artifacts such as regression to the mean. Interestingly, also the keys which were not directly affected by the manipulation were pressed significantly slower in the Key Switch condition. However, the difference here was much less pronounced than for affected keys (55 ms vs. 539 ms). Nevertheless, this may indicate some general slowing perhaps due to monitoring processes (Snyder & Logan, 2013) or slowing of neighboring keystrokes (Jordan, 1995). This speculation may be informed by the subjective ratings of participants which showed that the visual monitoring strategies changed after the key switch since participants reported to devote more visual attention to the hands and the keyboard when the keys were not in their original locations any longer. This self-report measure accords well with objective data assessed with eye-tracking technologies in Sperl and Cañal-Bruland (2020b) who also report an obvious shift in visual attention. Together, these results show that not only rule changes by means of verbal instructions or motor restrictions (Sperl & Cañal-Bruland, 2020b), but also changes that affect external equipment lead to severe performance decrements when pre-existing automatic behavior cannot be executed anymore. Having said this, it should be mentioned that because in the key switch condition participants were explicitly instructed to now press the respective keys at a changed location, this manipulation may also be seen as a rule change (which includes any types of changed task characteristics; cf. Newell, 1986).

Results further revealed that the experienced proactive interference not only affected mean times and errors, but also resulted in significant increases of the standard deviations for IKSI and errors on switched keys (see Table 6-1 and Figure 6-1). This finding provides additional support that individuals show considerable differences in how successfully they deal with proactive interference (Sperl & Cañal-Bruland, 2020b). To shed light on the origins and potential influencing factors leading to these individual differences, here, we examined to what degree test performance in the three subdimensions of inhibition (Friedman & Miyake, 2004), namely, resistance to proactive interference (Brown-Peterson Variant), resistance to distractor interference (Eriksen-Flanker Task) and prepotent response inhibition abilities (Stop-Signal Task) predict the amount of experienced proactive interference as evidenced by performance decrements after the key switch.

First, the analyses revealed that performance in the Stop-Signal Task predicted the amount of interference in the typing task. This means that the better participants suppressed prepotent response tendencies in the Stop-Signal Task, the less their performance (in terms of number of errors) deteriorated after the key switch. In other words, those participants who struggled to withhold prepotent responses in the Stop-Signal Task, had particular difficulties to react to the new constraints and tended to produce more errors on critical keys after the key switch. In fact, most errors on critical keys were caused by the fact that participants pressed the key at the original location, thereby very likely representing trials of failed response inhibition (for additional interest, see also *point of no return*, Logan, 2015; and *horse race model*, Verbruggen & Logan, 2009). Notably, while being associated with total time in the earlier study (Sperl &

Cañal-Bruland, 2020b), individual variables in the present study seem to be primarily associated with error variables. On the one hand, this finding replicates Sperl and Cañal-Bruland (2020b), thereby providing additional evidence that prepotent response inhibition seems to be of particular relevance in motor skill change. On the other hand, it extends previous findings by showing that this effect applies not only to rule changes that affect physical degrees of freedoms, but also external factors such as task equipment.

Second, resistance to proactive interference did not predict the amount of interference. That is, as predicted, interference experienced in the Brown-Peterson Task (built up from the first to the second and third list) was not associated with the amount of interference experienced in the typing task. Also this finding replicates the results found in Sperl and Cañal-Bruland (2020b). Together these two observations seem to indicate that the ability to inhibit prepotent action tendencies may be more important for successful motor skill change than being resistant to irrelevant memory contents. If this logic is sound participants' essential challenge in the present experimental task does not mainly seem to be keeping the changed demands (i.e. the fact, that the letters S and L are switched) cognitively present in mind, but rather to inhibit habitual (but undesired) action tendencies whenever they emerge (i.e. a wrong keypress at the original location).

Third, resistance to distractor interference significantly predicted the amount of interference in the regression analysis on total typing time. Specifically, better test performances in the Eriksen-Flanker Task were related to larger increases in total time required to type the paragraph after the key switch. This finding was neither predicted as no particular distractor stimuli were present in either condition nor does it intuitively make sense as poorer inhibitory abilities lead to less interference. We have currently no sensible explanation for this finding and feel that future research is needed to examine whether this finding is spurious in nature or whether resistance to distractor interference may truly predict the amount of interference.

Altogether, the different findings for the three subdimensions of inhibition combined with the fact that scores from the different tests were largely uncorrelated support the idea of inhibition as a multidimensional construct and underlines the necessity to treat it as such, particularly in empirical research (Friedman & Miyake, 2004). However, it should be kept in mind that the different tests for the three subdimensions of inhibition pose quite different task demands and perhaps more importantly, may also address different memory systems (Kane & Engle, 2000;

Verbruggen et al., 2008). The tests for prepotent response inhibition and resistance to distractor interference both require motor responses, whereas the Brown-Peterson Variant requires oral responses. Especially the demands of the Stop-Signal Task closely resemble those of the typing task where undesired movement tendencies need to be withheld. However, the typing task does not only require to inhibit wrong responses and stop erroneous action tendencies, but also involves a correction process and thus poses demands that go beyond those of the stop-signal paradigms which merely include a stop process (see also Boecker et al., 2013).

Furthermore, consisting of a word learning paradigm, the resistance to proactive interference test (i.e. the Brown-Peterson Variant) seems to mainly address declarative memory. Perhaps this difference may explain why resistance to proactive interference did neither predict the amount of interference in the current study nor in Sperl and Cañal-Bruland (2020b). We argue that – given its methodological peculiarities and reliance on declarative memory – possibly classic interference paradigms such as the Brown-Peterson Variant are not particularly sensitive to detect interference when changing motor skills that rely on proceduralized knowledge (see also notions on interference paradigms in the introduction). If true, then future research faces the challenge to develop specific tests that are sensitive to detect resistance to proactive interference in motor skill change in specific and tasks that rely on proceduralized knowledge in general. Conversely, it is also conceivable that the Brown-Peterson Variant may effectively detect resistance to proactive interference even in motor skill change if that task imposes higher demands on declarative memory. This is the case, for example, in motor sequence learning tasks in which participants usually learn and automatize motor commands for a task-specific motor sequence (Koedijker, Oudejans, & Beek, 2010; Tempel & Frings, 2016). Using a typing paradigm, this hypothesis could be tested if participants were asked to train a specific text and hence internalize and automatize both the memorized text as well as corresponding stimulus-dependent finger movement sequences, thereby also relying on declarative knowledge. If after automatization is accomplished, a rule change was induced, the change condition would hence not only address a procedural and stimulus-independent motor skill, but also specific declarative memory contents, perhaps making it more likely for the Brown-Peterson Variant to detect resistance to proactive interference. While exceeding the scope of the current study, future research is certainly needed to unravel the roles of declarative/cognitive interference and procedural/motor interference (Harnishfeger, 1995) and their potential interactions in motor skill change.

Finally, apart from the inhibitory functions, also baseline performance (i.e. the proficiency of typing skill) predicted the amount of proactive interference. More specifically, typists with faster baseline typing speeds were particularly affected by the rule change and experienced larger performance decrements. This finding is in agreement with the hypothesis and previous empirical evidence that a high proficiency is often beneficial to movement execution under regular conditions but detrimental under changed conditions (Sperl & Cañal-Bruland, 2020c). Even though we did not administer any test of automaticity, it is known that especially fast typists rely on strong proceduralized knowledge and automatisms (Logan, 2018), which in our task led visibly to the perseverative tendency to press a key at the original location. As participants certainly differ also regarding their degree of automaticity, it would be interesting for future research to assess automaticity with specific tests, such as e.g. dual-task paradigms (Magill & Anderson, 2016) and investigate also the contribution of this variable to successful motor skill change.

6.5 CONCLUSION

Taken together, proactive interference and inhibition play crucial roles in motor skill change tasks. Our results revealed that higher amounts of proactive interference are related to baseline performance, prepotent response inhibition and resistance to distractor interference. These findings support the idea of treating inhibition as a multidimensional construct. They further replicate previous research showing that the success in motor skill change is predicted by prepotent response inhibition. Hence, the ability to suppress strong automatic response tendencies seems to play a crucial role in overcoming interference, at least in motor tasks. It may thus be advisable to address this particular function when aiming to facilitate interference control (Sperl & Cañal-Bruland, 2020c). Clearly, more research is needed to scrutinize the roots of proactive interference in motor skill change in more depth. Once the underlying mechanisms are better understood, interventions may be developed in order to optimize and facilitate various types of skill change processes, be it in sports, rehabilitation or in the workplace.

APPENDIX

APPENDIX 6-A

Text stimulus used for the typing task:

Wenn ein Motorradfahrer zu schnell beschleunigt, läuft er Gefahr, sein Gleichgewicht zu verlieren und von der Maschine zu fallen. Aus den Samen vieler Pflanzen sprießen als erstes die Keimblätter, welche die Pflanze mit Energie versorgen. Musik erfüllt uns nicht nur mit Freude, sondern hilft vielen Leuten dabei, sich zu entspannen und die Sorgen loszulassen. Die Kinder spielten sehr fröhlich auf dem Pausenhof, als die Schulklingel ertönte und die Lehrerin sie ermahnte, sich möglichst schnell in die Klassenräume zu begeben. Der Vater kuschelte sich in seinen Lieblingssessel und seine Decke ein und begann sein Buch zu lesen. Die Vögel zwitscherten heute besonders fröhlich vor sich hin und erfüllten den Wald mit ihrem lieblichen Klang.

CHAPTER 7

ELECTROPHYSIOLOGICAL CORRELATES UNDERLYING INTERFERENCE CONTROL IN MOTOR TASKS

STUDY 4

Laura Sperl, Géza G. Ambrus, Jürgen M. Kaufmann, Stefan Schweinberger R. & Rouwen Cañal-Bruland

SUBMITTED AS

Sperl, L., Ambrus, G. G., Kaufmann, J. M., Schweinberger, S. R., & Cañal-Bruland, R. (submitted). Electrophysiological correlates underlying interference control in motor tasks.

7 ELECTROPHYSIOLOGICAL CORRELATES UNDERLYING INTERFERENCE CONTROL IN MOTOR TASKS

ABSTRACT

Changing pre-existing, automatized motor skills often requires interference control. *Prepotent response inhibition* – one subdimension of inhibition – has been theorized to be particularly associated with successful interference control in motor skills. Recent evidence suggests that different inhibition subdimensions elicit distinct ERP patterns (with larger P3 components for response inhibition). Therefore, we examined whether a similar ERP pattern would arise in a task demanding participants to overcome interference emerging from strong motor automatisms. This was realized within a typing paradigm involving a letter switch manipulation which is able to produce strong, immediate interference effects. Most importantly, stimulus-locked ERP analyses revealed an enhanced P3 component at frontal, central and most pronouncedly parietal sites for interference trials, in line with previous reported patterns for response inhibition. Together, different analyses provide first insights into the electrophysiological correlates of motor skill change, corroborating the pivotal role of response inhibition for successful interference control.

7.1 INTRODUCTION

The ability to deal with interference is an integral part of human cognitive functioning and particularly required in situations of response competition. Such a competition between action alternatives frequently emerges when strong automatisms trigger behavior that is highly dominant but counterproductive in a current situation. These automatisms are in principle functional as they do not put large demands on cognitive control over repetitive encounters. However, they can become problematic when we have to change or modify existing skills (Sperl & Cañal-Bruland, 2020c). Situations requiring to adapt to changes are omnipresent in our daily lives, such as when being confronted with new tools, techniques or physical changes, be it in the workplace, sports or other commonplace activities (Sperl & Cañal-Bruland, 2020b). In these situations, existing, often highly automatized motor components may compete with new, to-be-changed components, leading to proactive interference (Baxter et al., 2004; Panzer et al., 2005; Sperl & Cañal-Bruland, 2020a, 2020c). This interference may then cause unwanted performance decrements rendering the process of change particularly challenging (Carson & Collins, 2016; Sperl & Cañal-Bruland, 2020a). Hence, dealing with and overcoming proactive interference is crucial for successful skill change (Panzer et al., 2005; Sperl & Cañal-Bruland, 2020b).

Following the need to suppress unwanted action tendencies in such circumstances, interference control is closely intertwined with inhibitory functions (Friedman & Miyake, 2004; Levy & Anderson, 2002). In particular, for situations involving motor components, it has recently been shown that *response inhibition* seems to play a pivotal role in overcoming interference (Sperl & Cañal-Bruland, 2020b). In two recent studies, Sperl and colleagues found prepotent response inhibition abilities to be significantly related to success in a motor skill change task (Sperl & Cañal-Bruland, 2020b; Sperl, Gergeleit, & Cañal-Bruland, submitted). Performance in the Stop-Signal Task, which is known as a prominent tool to assess response inhibition (Logan, 2015), significantly predicted how well participants would adapt to a new rule in a motor task that disrupted participants' automatized motor behavior. More specifically, better response inhibition scores were associated with better motor skill change performance.

INHIBITION AS A MULTIDIMENSIONAL CONSTRUCT

Importantly, prepotent response inhibition is commonly understood as a subdimension of *inhibition* (Dempster & Brainerd, 1995; Diamond, 2013; Harnishfeger, 1995; Miyake et al., 2000). Friedman and Miyake (2004) scrutinized the nature of inhibition as a multidimensional construct and emphasized the issue that interference control and inhibition are often used as interchangeable terms, while, in fact, they are two distinct concepts (for more details see (Friedman & Miyake, 2004). Based on the original ideas by Nigg (2000), these authors postulate that inhibition consists of three distinct subdimensions. *Resistance to proactive interference* describes the ability to resist intruding memory contents which might have been previously important, but are no longer relevant to the task (such as in AB-AC word learning paradigms, where pair-wise learned stimulus words are paired to new target words after learning; see e.g., (Rosen & Engle, 1998). *Resistance to distractor interference* denotes the ability to suppress irrelevant stimuli from the environment (such as distractor stimuli in e.g., the Eriksen-Flanker Task, (Eriksen & Eriksen, 1974). *Prepotent response inhibition* describes the ability to suppress strong, automatic action tendencies (such as suppressing the tendency to read out the word, and instead name the color in the Stroop Task, Stroop, 1935).

PREPOTENT RESPONSE INHIBITION AND INTERFERENCE CONTROL

To the best of our knowledge, apart from the two recent studies mentioned above (Sperl & Cañal-Bruland, 2020b; Sperl, Gergeleit, & Cañal-Bruland, submitted), the relationship between prepotent response inhibition and success in motor skill change has never been investigated so far. In their most recent study, Sperl, Gergeleit, and Cañal-Bruland (submitted) investigated the role of inhibition for successful motor skill change by directly comparing the three subdimensions with each other. Therefore, they assessed participants' inhibition abilities by administering three distinct inhibition tests (Friedman & Miyake, 2004). The motor skill change task involved a typing task in which participants were instructed to first type short phrases as fast and accurately as possible in the habitual manner (triggering strong automatized motor behavior). In a second step, they were confronted with a keyboard on which two letters were switched in their position. This manipulation immediately disrupted participants' automatized typing behavior, leading to significant increases in the required typing times and errors (although only two out of 29 involved keys were affected). The amount of interference was determined by calculating the decline in typing performance from the baseline to the letter switch block. Among others, results revealed that prepotent response inhibition predicted the amount of interference, whereas resistance to proactive interference did not. These findings do not only support the idea of inhibition as a multidimensional construct (Friedman & Miyake, 2004), but also provide initial insights into the cognitive processes which might be involved when dealing with interference in motor tasks. Specifically, it seems that for situations requiring interference control, the ability to resist strong action tendencies might be more demanded than resisting intruding memory contents (such as the knowledge about the old rule). It may seem reasonable to assume that inhibition – at least in motor skill change tasks – occurs at a motor (behavioral) rather than at a cognitive (planning) level. However, it is difficult to directly dissociate motor inhibition from cognitive inhibition (Harnishfeger, 1995) at a behavioral level, as the majority of cognitive tasks involve overt motor responses (which is true for all classic button-press experiments, but also for tasks requiring oral responses) and cognitive processes are likewise highly involved in motor responses (for empirical approaches to dissociate the two processes see, Bernal & Altman, 2009; Burle et al., 2004; Smith et al., 2008).

From a time course perspective, it has been suggested to further distinguish between proactive inhibition and reactive inhibition. *Proactive inhibition* is suggested to comprise a preparatory process and thus a form of control which occurs already prior to the conflict situation (Di Russo et al., 2016; Kaiser & Schuetz-Bosbach, 2019; Meyer & Bucci, 2016), and incorporates to a larger extent a planned action strategy (Angelini et al., 2016). *Reactive inhibition* involves stopping a motor response that is already in progress (Meyer & Bucci, 2016), or reacting to a stop signal which has just appeared (Angelini et al., 2016; Aron, 2011). Hence this type of inhibition comes into play only after a conflict has been detected (Kaiser & Schuetz-Bosbach, 2019; Lavallee et al., 2014). For proactive inhibition it is therefore important to maintain the goal-relevant information in memory in order to be prepared for future conflict situation (Sulpizio et al., 2017). In the reported skill change paradigm both processes are conceivable to be involved, as the task requires to constantly keep the changed rule in mind, but nevertheless due to a remaining unpredictability of critical stimuli and strong automatisms, wrong movements are sometimes already initiated and then need to be stopped.

Next to the fact that previous research could not distinguish between proactive and reactive inhibition processes, another limitation resides in the fact that the paradigms used thus far administered mainly correlative and regressive approaches that examined the relationship between inhibition test performance and interference in the motor task. One methodological approach to overcome these limitations is the use of EEG which allows an on-line assessment of the neuro-cognitive processes which are at play in situations of interference control. Specifically, for our purpose, EEG offers the opportunity to scrutinize the role of response inhibition in interference control in motor tasks at an electrophysiological level by examining event-related potentials (ERPs).

ELECTROPHYSIOLOGICAL CORRELATES OF RESPONSE INHIBITION

ERP studies have a long-standing history in the research of the neuroscientific bases of cognitive mechanisms and response inhibition has been widely investigated over the past decades with this technique (for a review, see Huster et al., 2013). Tests to study response inhibition often include Go/NoGo paradigms (Brydges et al., 2012; Falkenstein et al., 1999; Kiefer et al., 1998), flanker paradigms (Groom & Cragg, 2015; Xie et al., 2017) or stop paradigms such as the Stop-Signal Task (Etchell et al., 2012; Kok et al., 2004; Wessel & Aron, 2015). Repeated evidence has been reported for the N2 and the P3 components which have been suggested to be involved in processes of response inhibition (Dimoska et al., 2006; Falkenstein et al., 1999; Groom & Cragg, 2015; Kiefer et al., 1998; Kok et al., 2004; Salisbury et al., 2004; Smith et al., 2007, 2008; van Boxtel et al., 2001; Wessel & Aron, 2015). Typically, these components were observed to be larger in stop vs. go trials, with effects that were most pronounced over fronto-central (Dimoska et al., 2006; Greenhouse & Wessel, 2013; Wessel & Aron, 2015) and/or centro-parietal areas (Falkenstein et al., 1999; Kiefer et al., 1998; Ramautar et al., 2004; Smith et al., 2008). Possibly, the N2 in this context reflects some kind of response conflict detection or monitoring, whereas the P3 may reflect the actual process of response inhibition (Groom & Cragg, 2015; Kok et al., 2004) or the inhibition of an overt motor response (Smith et al., 2008). In contrast, others suggest that the P3 rather than the N2 reflects both response inhibition as well as the conflict between competing responses (Smith et al., 2007). Moreover, the P3 is observed to be larger in successful vs. failed stop trials and may thus involve some sort of error-related activity or reflect an evaluation process of the inhibitory activity (Kok et al., 2004; Ramautar et al., 2004). It is also discussed whether the P3 might be especially sensitive to motor responses and to some extent reflects processes of motor response execution (Boulinguez et al., 2009; Smith et al., 2008). Considering these mixed findings, it should be kept in mind that the reported studies often varied in methodological aspects and also pursued different research questions (such as investigating inhibition vs. control conditions, successful or unsuccessful stopping or effects of stimulus probability or modality; see e.g, Dimoska et al., 2006; Kok et al., 2004; Ramautar et al., 2004; Wessel & Aron, 2015).

In the context of response inhibition, two studies were particularly inspiring for our research. First, a recent study by Xie et al. (2017) aimed to specifically unravel the electrophysiological signatures of three different inhibition dimensions by means of ERPs. These authors denote that even if different inhibition dimensions may be distinguishable at a conceptual level, the neural distinctions between such dimensions are not well investigated yet (Xie et al., 2017; for exceptions, see, e.g., Brydges et al., 2012; Jongen & Jonkman, 2008; Vuillier et al., 2016). To this end, Xie et al. (2017) designed three modified versions of the Eriksen-Flanker Task, each of which addressed one of three subdimensions of inhibition. Even if labelled differently, these three subdimensions highly overlap with those postulated by Friedman and Miyake (2004). *Rule (cognitive) inhibition* is required to suppress irrelevant information or invalid rules from working memory, thus sharing many features with resistance to proactive interference which is also related to irrelevant memory contents. *Flanker inhibition,* in turn, involves ignoring irrelevant stimuli, and thus is highly comparable to resistance to distractor interference (note that this concept is also dubbed as interference control by the authors, which is in contrast to claims by Friedman and Miyake, (2004). *Response inhibition* comprises more or less the same concept as described for prepotent response inhibition following Friedman and Miyake (2004) with the difference that Xie et al. (2017) refer to withholding one or more unwanted responses while implementing an alternative response. In fact, this is characteristic for most motor skill change tasks, where an old behavioral component is replaced by a new one rather than omitted completely (Sperl & Cañal-Bruland, 2020b). To briefly summarize the core findings of this study (Xie et al., 2017), each of the three different inhibition dimensions elicited a distinct ERP pattern. All observations were determined by comparing the averaged ERPs of the respective inhibition with a non-inhibition condition, time-locked to the onset of the stimulus. In a nutshell, for the flanker inhibition condition a larger frontal N2 component was observed. The rule (cognitive) inhibition generated a larger posterior N1 and a larger frontal P3a (the latter being supposed to reflect the novel stimulus-reaction pairing). Finally, and most importantly, response inhibition was characterized by a larger posterior P3b component. According to the authors, this reflects the act of suppressing the irrelevant action and implementing the relevant response. Of course, and also according to the authors, it cannot be fully excluded that the three different test versions addressed more than one dimension of inhibition (although difference waves may help here) and probably also involved other cognitive abilities apart from inhibition. The study provided first valuable insights into the electrophysiological correlates of the multidimensionality of inhibition. Furthermore, its results are in line with previously reported findings that suggest a relation between response inhibition and the P3 component

(Dimoska et al., 2006; Falkenstein et al., 1999; Groom & Cragg, 2015; Salisbury et al., 2004; Smith et al., 2007, 2008).

In the second pertinent study, Krämer et al. (2011) compared the electrophysiological correlates of so-called stop-signal with change-signal tasks (for a review, see Boecker et al., 2013). The stop-signal task usually involves withholding a response in indicated trials. The change-signal task, however, comprises a change of motor plans, that is withholding a response and executing an alternative response instead. As mentioned above, this is actually the same demand as for many motor skill change tasks. Results revealed that in contrast to the stop-signal task, change-signal tasks did not elicit the inhibition-related N2 component, whereas the P3 was present for both task types. This accords well with the findings by Xie et al. (2017) whose response inhibition task also required an alternative response, highlighting the particular involvement of the P3 component for change tasks.

In fact, in a long-standing research history, the P3 component has been reported to be evoked by novel, deviant, infrequent or unpredicted stimuli, such as in oddball paradigms (for a review, see Polich, 2007). Moreover, it is most pronounced for stimuli that are of high task relevance (Barry et al., 2020). Whereas the frontally maximal P3a seems to be elicited by stimuli which are completely unexpected, the parietally maximal P3b component seems to occur when changes in the stimuli are a) task-relevant and b) in some sense closing a perceptual epoch. According to Donchin (1981), the P3 wave is associated with strategic rather than tactical responses. Whereas a tactical response deals with a current, unexpected situation, a strategic response involves an a-priori preparation for irregular situations (Luck, 2014). This accords well with the demands posed in experimental paradigms for motor skill change described earlier (Sperl & Cañal-Bruland, 2020b) where participants are indeed aware of the rule change a-priori and must strategically apply the new rule throughout a whole task block. Hence, the stimuli in these motor skill change paradigms are in some sense expected, but nevertheless still infrequent and less predictable in their occurrence. To sum up, the reported studies provide converging evidence that especially the P3 component is closely related to response inhibition and seems to be especially characteristic for inhibition situations which call for alternative actions (Krämer et al., 2011; Xie et al., 2017).

THE PRESENT STUDY

If response inhibition plays a particular role also in interference control in motor skill change, at an electrophysiological level, this should be accompanied by an enhanced P3 in trials demanding interference control compared to control trials. To test this, in the present study, we induced proactive interference in an automatized motor skill by applying a letter switch manipulation in a typing task. This provided several advantages: First, typing reflects a highly automatized motor skill which nowadays is mastered by a large part of the population (Logan, 2018). Furthermore, a small manipulation such as a letter switch (Gordon et al., 1994; Jordan, 1995; Parasher et al., 2001; Yamaguchi & Logan, 2014) is able to immediately disrupt participants in their automatized skill. Third, typing represents a complex motor behavior, but one which nevertheless – unlike many other complex motor tasks – can be combined with EEG. In the current study, in the baseline condition, participants first typed single words as accurately and fast as possible in the regular manner. In the subsequent condition, they performed the same task following a new rule in which two letters were digitally switched in their position. Electrophysiological correlates of interference were investigated by comparing ERPs in the Baseline vs. Rule Change condition both at a stimulus-locked (word onset) as well as at a response-locked (keystroke) basis.

If the electrophysiological data are in line with the behavioral data emphasizing the particular role of prepotent response inhibition, a larger P3 should be observed in trials involving a switched letter in the Rule Change condition compared to the matched control trials in the Baseline. This was examined via stimulus-locked analyses. In addition, we conducted response-locked analyses for which we pursued a more exploratory approach by comparing electrophysiological brain activity in the pre-response interval before a critical keypress in both conditions. Finally, we examined potential relationships between the three different subdimension of inhibition (measured by performance in three distinct inhibition tests) and both the behavioral performance outcomes and the amplitude of the P3 component.

7.2 METHODS

PARTICIPANTS

Twenty-two participants (12 female, mean age: 25.3, *SD* = 2.9, range: 20 – 30 years) contributed data to the experiment[6]. Inclusion criteria were a) an age between 18 to 30 years, b) being right-handed, c) being a native speaker of German, d) not suffering from any neurological or psychiatric diseases according to self-report, and e) being able to type at a minimum speed of 30 words per minute. Data from three participants had to be removed from the sample dataset as it turned out during the experiment that they did not meet these inclusion criteria. Average typing speed was 256 characters per minute (51 words per minute, respectively). Participants received financial reward (17.50 €) or course credit for their participation. The experiment was approved by the ethics committee of the Faculty of Social and Behavioural Sciences of the Friedrich Schiller University Jena (reference: FSV 19/071).

MATERIALS

Inhibition Tests

Brown-Peterson Variant. To examine resistance to proactive interference (PI) we conducted a slightly adapted version of a word recall paradigm based on Kane and Engle (2000), adjusted for German native speakers. This version contains one stimulus set consisting of a practice list, three PI build-up lists with words from the same semantic category (here: animals) and one PI release list with words from another semantic category (here: professions). As in the original version, these items originate from the lists of category norms by Battig and Montague (1969) and a list consists of ten items (for the complete lists, see (Sperl & Cañal-Bruland, 2020b). The words are presented one at a time at an interval of 2000 ms (1750 ms stimulus presentation and 250 ms interstimulus interval) centered on the screen (font size: 60, black on white background). During word presentation, participants read each presented word aloud. After

[6] An a priori power analysis using an alpha of .05, a power of .80 and two-tailed testing (inhibition vs. non-inhibition condition) revealed a minimum required sample size of n=9. This power analysis is based on Xie et al. (2017), who reported an effect size *d* = 1.076 for the comparison of mean amplitude of P3b in the inhibition vs. non-inhibition condition.

each list, they perform a rehearsal-prevention task for 16 seconds (i.e., seeing a letter-number-combination, e.g., G-45, and continue this combination forward counting, i.e., "G-45, H-46, I-47" and so on). Participants then have 20 seconds to recall all items they remember from the previous list. The experimenter checks the answers simultaneously and records any intrusions on a test protocol. The background of the screen then turns into red color, signaling the participant to stop the recall. After a break of 15 seconds this procedure is repeated for the remaining lists. Resistance to proactive interference is typically calculated as a proportion of loss from List 1 using the formula [$List_X$ – $List_1$] / $List_1$. This computation generates two separate values (i.e., dependent measures) for each of the two proactive interference build-up lists ($PI_{List\ 2}$ and $PI_{List\ 3}$) (see also Kane & Engle, 2000).

Eriksen-Flanker Task. To assess resistance to distractor interference, the Eriksen-Flanker Task (Eriksen & Eriksen, 1974) was conducted. In this test, participants have to react as fast and as accurately as possible to a target letter. Whenever the target letter is "X" or "C", they must press the left key, when the target letter is "V" or "B", they must press the right key. This target letter is embedded into a line of 4 identical distractor letters (also "X", "C", "V" or "B"). In compatible trials the target and distractor letters would require the same reaction key (e.g., XXCXX), in incompatible trials, however, a different response would be correct (e.g., XXVXX). In only a few cases, the target letter is displayed without distractor letters. The task consisted of a practice block of 32 trials and 4 experimental blocks of 40 trials. Before each trial a fixation cross of 500 ms was displayed in the center of the screen. The stimuli were displayed in a font size of 40 and remained until a response key was pressed, maximum reaction time was 2000 ms. Response feedback was given via green colors after each response. Resistance to distractor interference was computed using the difference of RT on incompatible and compatible trials (only correct trials involved).

Stop-Signal Task. To measure prepotent response inhibition abilities, we applied the Stop-Signal Task as a well-established tool to measure this type of inhibition (Logan, 2015). We used the STOP-IT software provided by Verbruggen et al. (2008), which is accessible on the Open Science Framework platform (https://osf.io/wuhpv). In this task, participants perform a simple decision task with the instruction to press a respective button (right or left) when one of two geometric forms is presented (circle vs. square). However, when during a trial an auditory signal tone is played, participants are instructed to immediately interrupt their current response and to refrain from pressing the response button in this trial. In the present study, participants performed a practice block of 1x32 trials, followed by the main task consisting of 3 blocks of 64 trials with a short break after each block. The time between the stimulus and the stop signal (stop signal delay) typically varies depending of the participant's test performance. The stop signal delay starts at a default value of 250 ms and increases by 50 ms after successful inhibition trials and decreases by 50 ms after unsuccessful trials. This adaptive testing allows a reliable estimation of the individual stop signal reaction time (SSRT), which enables to estimate the covert latency of the stop process (Verbruggen et al., 2008). Lower values represent better response inhibition. Here, SSRT was estimated via the integration method (for a detailed description see (Verbruggen et al., 2013).

Typing Task

Hardware. The typing task was conducted on a computer with a standard German QWERTZ keyboard (Microsoft Wired Keyboard 400). In order to minimize eye movements, an external 5 inch LCD monitor (Waveshare) was placed directly above the keyboard (see Figure 7-1). This monitor presented the to-be-typed stimuli in direct proximity to the keyboard, thus enabling the participants to directly see keyboard and monitor in the visual field without the need to move the head when switching visual attention between monitor and keyboard. Note that visual control of finger movements at least in the rule change condition in our experimental paradigm is inevitable even in touch-typists. A chin rest (adjustable in height and inclination) was designed to restrict additional head movements. Besides avoidance of head movements, this novel set-up enabled us to reduce the number of rejected trials due to extensive eye movements, thus increasing signal-to-noise ratio.

Figure 7-1. Typing set-up involving the external LCD monitor in direct proximity to the keyboard.

Word Stimuli. The word stimuli consisted of German words (word length range: 3 – 8 characters). Words including the German letter ß were excluded as this letter is located in the row of special signs. All words (including nouns) were presented in lower case letters to rule out the need to use the shift key as an additional keystroke before the actual first letter. The complete set of word stimuli (240 words) can be classified into three categories: no critical letters, critical letter in first position and critical letter in fifth position (80 words each), see also Table 7-1. We considered that placing the critical letters (which will later be switched in the Rule Change condition) in the first position enables us to measure an ERP which is uncontaminated by previous keystrokes and allows both stimulus- and response-locked analyses (Pinet et al., 2015; Pinet et al., 2019; Scaltritti et al., 2018). However, neither presence nor position of the critical letter should be predictable for participants as this would dramatically reduce proactive interference. Moreover, interference was assumed to be particularly high when the critical letter was located later in the word when typing flow has already built up and triggers prepotent responses. For that reason, we also included words with critical letters in the fifth position and words without critical letters at all. Note that for the critical letter in the fifth position, only response-locked analyses were conducted.

As critical letters, the letters S and L were chosen[7] and were equally distributed among the critical words. The complete stimulus list can be found in Appendix 7-A (Table 7-3). To compare the two conditions irrespective of any influence of stimulus difficulty on typing performance, we applied the same stimulus material in both Baseline and Rule Change block (A. M. Anderson et al., 2009; Gordon et al., 1994; Parasher et al., 2001; Sperl & Cañal-Bruland, 2020c).

Table 7-1. Overview of item categories.

critical letters [S]/[L]	**number**	**word examples**
none	80	warum, aber, während
position 1	80 (40x L, 40x S)	leider, sieben, sand
position 5	80 (40x L, 40x S)	beeilen, phrase, genesen

Typing software. A script was programmed with PsychoPy 3.6 to present stimulus words, measure typing performance, i.e., Interkeystroke Interval (IKSI; time from one keystroke to the next one) and errors, and send stimulus- and response-related triggers to the EEG amplifier. The stimulus words were displayed centered in white color (font: MS Reference Sans Serif, font size: 120) on black background. The current to-be-typed letter was always highlighted by a grey frame. Correctly typed letters turned into green, incorrectly typed letters turned into red color, informing the typist about the error and the need to correct the last entry by pressing the correct key to continue (no backspace key required). Before each stimulus word, a fixation cross of 1700 ms was displayed. Written instructions were displayed on the monitor before each block.

EEG recording. Electrophysiological data was recorded continuously using a 32-channel EEG with BioSemi Active II system (BioSemi, Amsterdam, The Netherlands) with a 512 Hz sample rate from direct current to 155 Hz. Recording sites were Fz, Cz, Pz, Iz, FP1, FP2, F3, F4, C3, C4, P3, P4, O1, O2, F7, F8, T7, T8, P7, P8, F9, F10, FT9, FT10, TP9, TP10, P9, P10, PO9, PO10, I1, I2.

[7] The reasoning behind the decision to use the letters S and L for the letter switch was the following: a) they have an approximate similar frequency in German language, b) their position on the QWERTZ keyboard is symmetrical and thus, they pose comparable biomechanical demands, c) their position is fairly distant from each other which ensures that even in non-touch-typists they are pressed by different fingers (see also Parasher et al., 2001) and d) findings from a recently conducted study revealed that the switch of these two letters was able to produce effects of proactive interference (Sperl et al., submitted).

Note that the BioSemi system uses a so-called "zero-Ref" system which uses two additional electrodes (CMS and DRL) instead of reference and ground electrode (see also www.biosemi.com/faq/cms&drl.htm). Four additional electrodes (one each at the outer canthi of both eyes, and one each above and below the right eye, respectively) were used to record EOG.

DESIGN AND PROCEDURE

Prior to the experiment, participants conducted a short 1-min online typing test to ensure that they met the criterion of minimum typing speed. On arrival in the lab, participants provided informed consent and were briefed about the general procedure of the experiment. The experiment then started with the inhibition tests in the following order: Brown-Peterson Variant, Eriksen-Flanker Task and Stop-Signal Task. After these inhibition tests (approximately 30 minutes), the EEG set up was prepared by placing the EEG cap and electrodes on the participant's head and connecting the electrodes with a gel to the scalp. After this, participants were seated in an electrically shielded and sound-attenuated cabin (IAC™CT-400) to start the main experimental task while EEG was recorded.

Baseline. In the Baseline condition, participants had to type the 240 stimulus words (in random order) in the habitual manner. To familiarize them with the task, participants absolved a short practice list of eight stimuli. Participants were invited to take a short break after every 20 trials.

Rule Change. In the Rule Change block, the critical rule change was introduced to the participants who now typed the same 240 words (again presented in random order) under the changed condition. This involved the digital letter position switch of the letters "S" and "L". Put simply, this means that whenever a "S" appeared in a word they now had to press the "L" key and vice versa. Again, to familiarize the participants with the task, they started this block with a short practice block of eight stimuli and short breaks after every 20 trials were included.

This EEG-recorded part of the experiment (typing task including Baseline and Rule Change) lasted around 25 to 40 minutes.

DATA ANALYSIS

Behavioral data were pre-processed in R Studio 1.1.419 and statistically analyzed using the software JASP 0.10.2. To examine changes in typing performance a 2 (block: Baseline vs. Rule Change) x 2 (key type: regular vs. critical) x 2 (position: 1 vs. 5) ANOVA on both IKSI and errors on critical keys was conducted. Effect sizes were calculated as partial eta-squares *(*η_p^2*)*. Pearson's correlation analyses were conducted to test for potential relationships between the inhibition tests and the amount of interference (always calculated as the difference in typing performance from Rule Change to Baseline), P3 mean amplitude as well as the inhibition tests among each other.

EEG raw data files (.bdf files) were pre-processed in BESA Research 7.0 administering EOG-based artifact correction (HEOG threshold: 150 µV, VEOG threshold: 250 µV) and filtering (0.3 Hz to 30 Hz). These pre-processed data files were converted to .fif files and continued processing in Spyder 3.7 using the MNE package (see https://mne.tools). There, epochs segments were extracted for correct trials (reflecting successful inhibition), locked onto the stimulus onset or response, and baseline-corrected. Stimulus-locked epochs ranged from -200 to 1500 ms (baseline period: -200 to 0 ms) and response-locked epochs ranged from -800 to 100 ms (baseline period: 0 to 100 ms). Artifact rejection parameters were based on peak-to-peak amplitude and set to 100 µV. Rejecting bad trials and including only trials with correct response, 93 % of the trials could be used for stimulus-locked analyses (on average over all participants, 77.0/80 total trials in Baseline, and 72.3/80 trials in Rule Change) and 72 % of the trials could be used for response-locked analyses (position 1: 64.8/80 trials in Baseline, 57.9/80 trials in Rule Change; position 5: 59.8/80 trials in Baseline, 48.3/80 trials in Rule Change). Statistical analyses were conducted in Spyder 3.7 and JASP 0.10.2. For stimulus-locked analyses mean amplitude was calculated in a time window of 300 to 500 ms encompassing the P3 component, as well as for a late interval (600 to 1200 ms). For response-locked analyses, a more exploratory approach was pursued. As the intention was not to observe a specific component but rather to investigate the general voltage course before the participant's response, the pre-response interval was split into three consecutive and equidistant sub-intervals from -600 to -400 ms, -400 to -200 ms and -200 to 0 ms, for which mean amplitudes were computed. In both, stimulus- and response-locked analyses, these mean amplitudes over the respective time windows were then analyzed conducting separate 2 (block: Baseline vs. Rule Change) x 3 (anteriority: frontal vs. central vs. parietal) x 3 (laterality: left, central, right) ANOVAs. In case of violation of the sphericity assumption, Huynh-Feldt (Huynh & Feldt, 1976) corrected p-values were used and ε-values reported. Note that, since we were interested in a letter-unspecific effect of letter switch, we discriminated at the level of critical vs. non-critical letters in the analyses, but not between the identities (S or L) of the critical letter.

7.3 RESULTS

BEHAVIORAL DATA

Typing Performance

As illustrated in Figure 7-2, both IKSI and errors on switched letters increased substantially from Baseline to Rule Change.

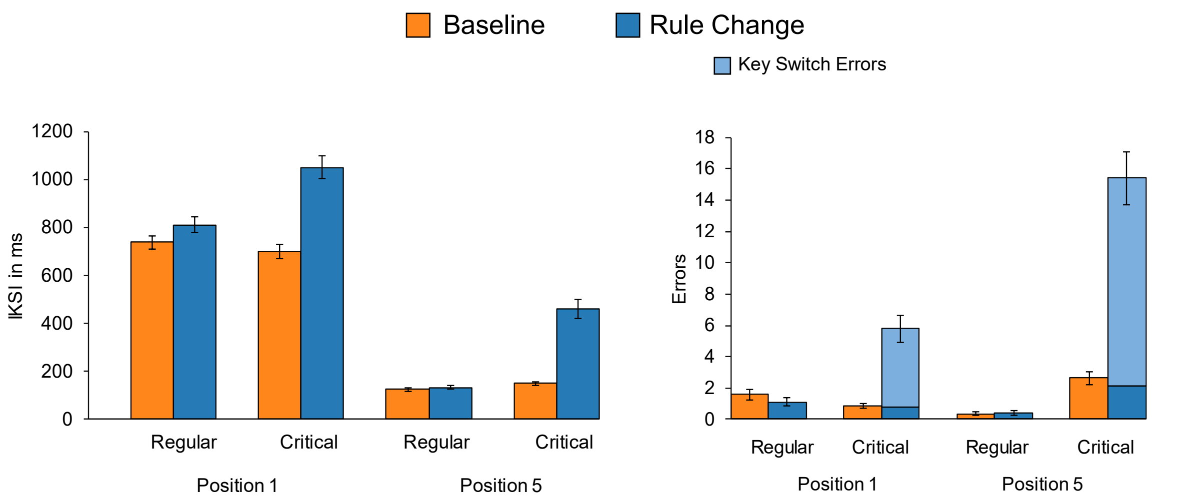


Figure 7-2. Interkeystroke Intervals (left) and errors (right) for keystrokes in Baseline vs. Rule Change. Critical keys involve keys which were affected by the letter switch (i.e., letter S and L), regular keys all remaining keys. The critical letter was either on first or fifth position in the word. Regular keys on first or fifth position served as control keys. For errors made in the Rule Change condition, the portion of errors in which the original key position was pressed are marked separately in light blue (letter switch errors). Error bars indicate standard errors.

A 2 (block: Baseline vs. Rule Change) x 2 (key type: regular vs. critical) x 2 (position: 1 vs. 5) ANOVA on IKSI confirmed this observation. First, this ANOVA revealed a main effect of block (F[1,18] = 117.246, p < .001, η_p^2 = .867), and a main effect of key type (F[1,18] = 85.098, p < .001, η_p^2 = .825), which were qualified by a significant block by key type interaction (F[1,18] = 127.160, p < .001, η_p^2 = .876), revealing that there was a significant increase in IKSI for the keys which were affected by the letter switch compared to the other keys. This ANOVA also revealed a significant main effect for position (F[1,18] = 692.766, p < .001, η_p^2 = .975), meaning that IKSI for the first letter was higher than for the fifth letter in the word. This effect was accompanied by significant key type by position (F[1,18] = 32.979, p < .001, η_p^2 = .647) and block by position interactions ($F[1,18] = 11.151$, $p = .004$, $\eta_p^2 = .382$), indicating a higher increase in RT when the critical letter was in first position. The three-way interaction, however, was not statistically significant ($F[1,18] = 1295$, $p = .270$, $\eta_p^2 = .067$).[8]

An equivalent ANOVA was run for errors. Also regarding errors, there was a main effect for block ($F[1,18] = 47.871$, $p < .001$, $\eta_p^2 = .727$), for key type ($F[1,18] = 76.201$, $p < .001$, $\eta_p^2 = .809$) and letter position ($F[1,18] = 38.664$, $p < .001$, $\eta_p^2 = .682$). All three possible two-way interactions (block x position: $F[1,18] = 27.453$, $p < .001$, $\eta_p^2 = .604$; block x key type: $F[1,18] = 55.423$, $p < .001$, $\eta_p^2 = .755$; position x key type: ($F[1,18] = 72.701$, $p < .001$, $\eta_p^2 = .802$) as well as the three-way interaction ($F[1,18] = 22.265$, $p < .001$, $\eta_p^2 = .553$) were significant, indicating that error increase from Baseline to Rule Change was driven by critical keys and largest if critical keys were in the fifth position (see also Figure 7-2).

Inhibition tests

Correlation analyses neither revealed any significant relationship between the inhibition tests and the amount of interference, nor between the inhibition test parameters among each other (all *p*s > .05). A complete correlation matrix can be inspected in Appendix 7-B (Table 7-4).

EEG DATA

Stimulus-locked Analyses

All ERP analyses refer to correct keystrokes, thus reflecting successful inhibition. ERP plots and scalp maps can be inspected in Figure 7-3, mean amplitudes are plotted in Figure 7-4. The 2 (block: Baseline vs. Rule Change) x 3 (anteriority: frontal vs. central vs. parietal) x 3 (laterality: left, central, right) ANOVA on mean amplitudes in the time window 300 to 500 ms for critical

[8] For additional interest, to examine change in variability of typing performance, we performed an equivalent ANOVA on standard deviations of IKSI and observed an interesting pattern also for this dependent variable. There was a significant main effect of block ($F(1,18) = 76.543$, $p < .001$, $\eta_p^2 = .810$), key type ($F(1,18) = 42.028$, $p < .001$, $\eta_p^2 = .700$) as well as a block x key type interaction ($F(1,18) = 53.912$, $p < .001$, $\eta_p^2 = .750$), meaning that particularly for critical keys the SD of IKSI increased from Baseline to Rule Change. Moreover, this ANOVA revealed a significant interaction of position and key type ($F(1,18) = 21.553$, $p < .001$, $\eta_p^2 = .545$) and a significant three-way interaction ($F(1,18) = 13.071$, $p = .002$, $\eta_p^2 = .421$; all remaining effects $p \geq .765$). This suggests, i.a., that the performance decline due to proactive interference was very different in its extent across participants (see also Sperl & Cañal-Bruland, 2020c).

keys on position 1 revealed significant main effects for all three factors (block: $F[1,18] = 21.096$, $p < .001$, $\eta_p^2 = .540$; anteriority: $F[2,36] = 44.774$, $p < .001$, $\eta_p^2 = .713$, $\varepsilon = .626$; laterality: $F[2,36] = 10.728$, $p < .001$, $\eta_p^2 = .373$). Moreover, this ANOVA revealed significant interactions for block and laterality ($F[2,36] = 8.216$, $p < .001$, $\eta_p^2 = .313$), anteriority and laterality ($F[4,72] = 16.754$, $p < .001$, $\eta_p^2 = .482$, $\varepsilon = .725$) and a significant three-way interaction ($F[4,72] = 5.370$, $p < .001$, $\eta_p^2 = .230$, $\varepsilon = .956$). No significant interaction was present for block and anteriority ($F[2,36] = 1.538$, $p = .232$, $\eta_p^2 = .079$, $\varepsilon = .778$).

As far as the later time window (600 to 1200 ms) is concerned, the 2 (block: Baseline vs. Rule Change) x 3 (anteriority: frontal vs. central vs. parietal) x 3 (laterality: left, central, right) ANOVA on mean amplitudes revealed significant main effects for block ($F[1,18] = 87.466$, $p < .001$, $\eta_p^2 = .829$) and anteriority ($F[2,36] = 41.780$, $p < .001$, $\eta_p^2 = .699$, $\varepsilon = .797$), but not for laterality ($F[2,36] = 0.865$, $p = .430$, $\eta_p^2 = .046$). Both effects were qualified by significant anteriority by laterality ($F[4,72] = 12.779$, $p < .001$, $\eta_p^2 = .415$, $\varepsilon = .809$) and block by laterality interactions ($F[2,36] = 27.869$, $p < .001$, $\eta_p^2 = .608$), indicating that the change in mean amplitudes were most prominent on central and right electrodes. In contrast, there was no block by anteriority interaction ($F[2,36] = 1.144$, $p = .310$, $\eta_p^2 = .060$, $\varepsilon = .620$). Also the three-way interaction was statistically significant ($F[4,72] = 3.336$, $p = .015$, $\eta_p^2 = .156$). No significant correlations between the performance in the inhibition tests and the difference in mean amplitude of P3 could be observed (see also Appendix 7-B, Table 7-4).

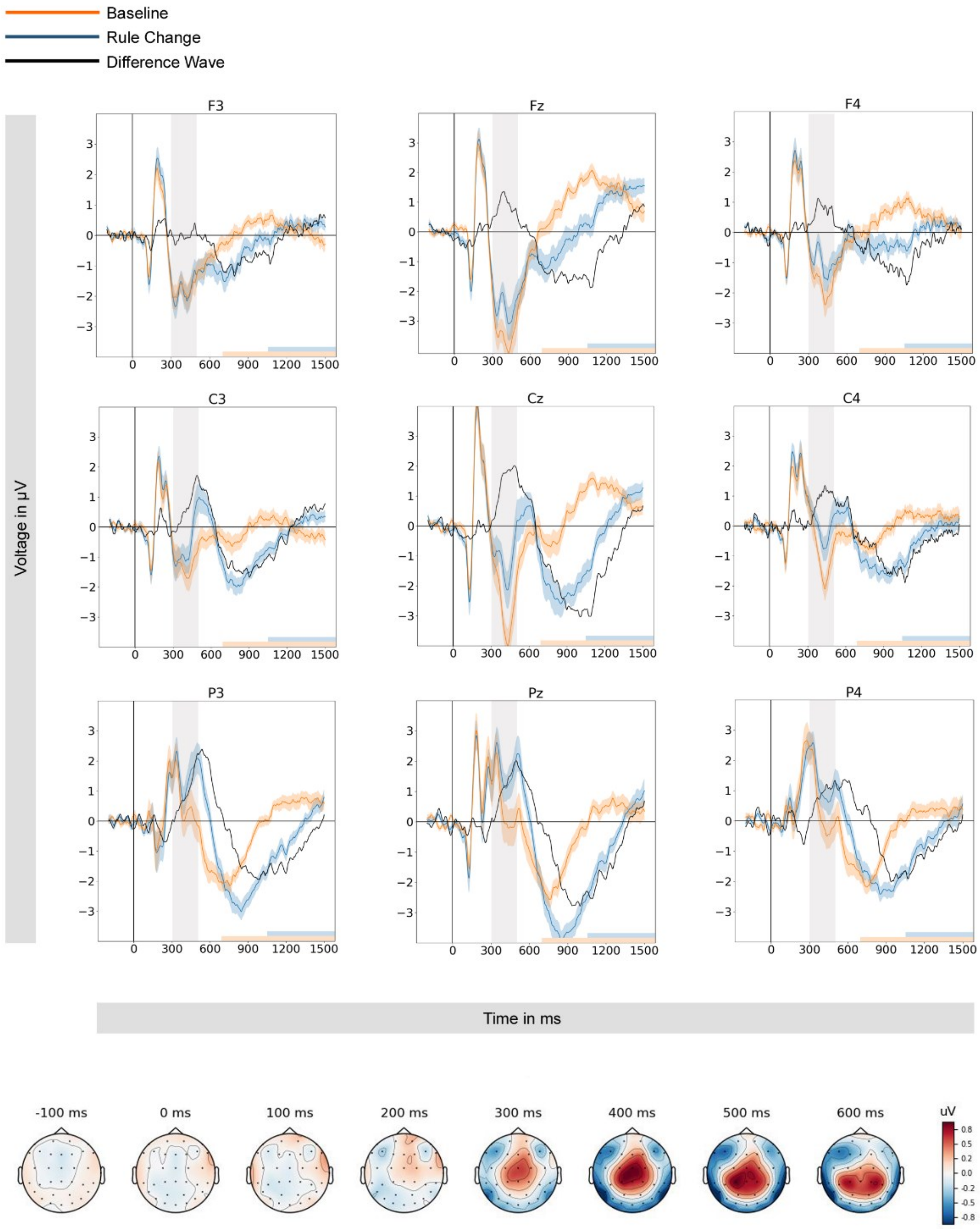


Figure 7-3. Top: Stimulus-locked ERPs (-200 ms to 1500 ms) and difference wave for correct keystrokes of critical letter in first position (only followed by correct entries). Transparent ribbons indicate standard errors. Grey vertical transparent bars mark the time interval between 300 and 500 ms characterizing the P3 component window. Horizontal bars on the right bottom indicate average initiation of typing across all trials in Baseline (orange) and Rule Change (blue). Bottom: Scalp distribution of difference wave from -100 ms to 600 ms.

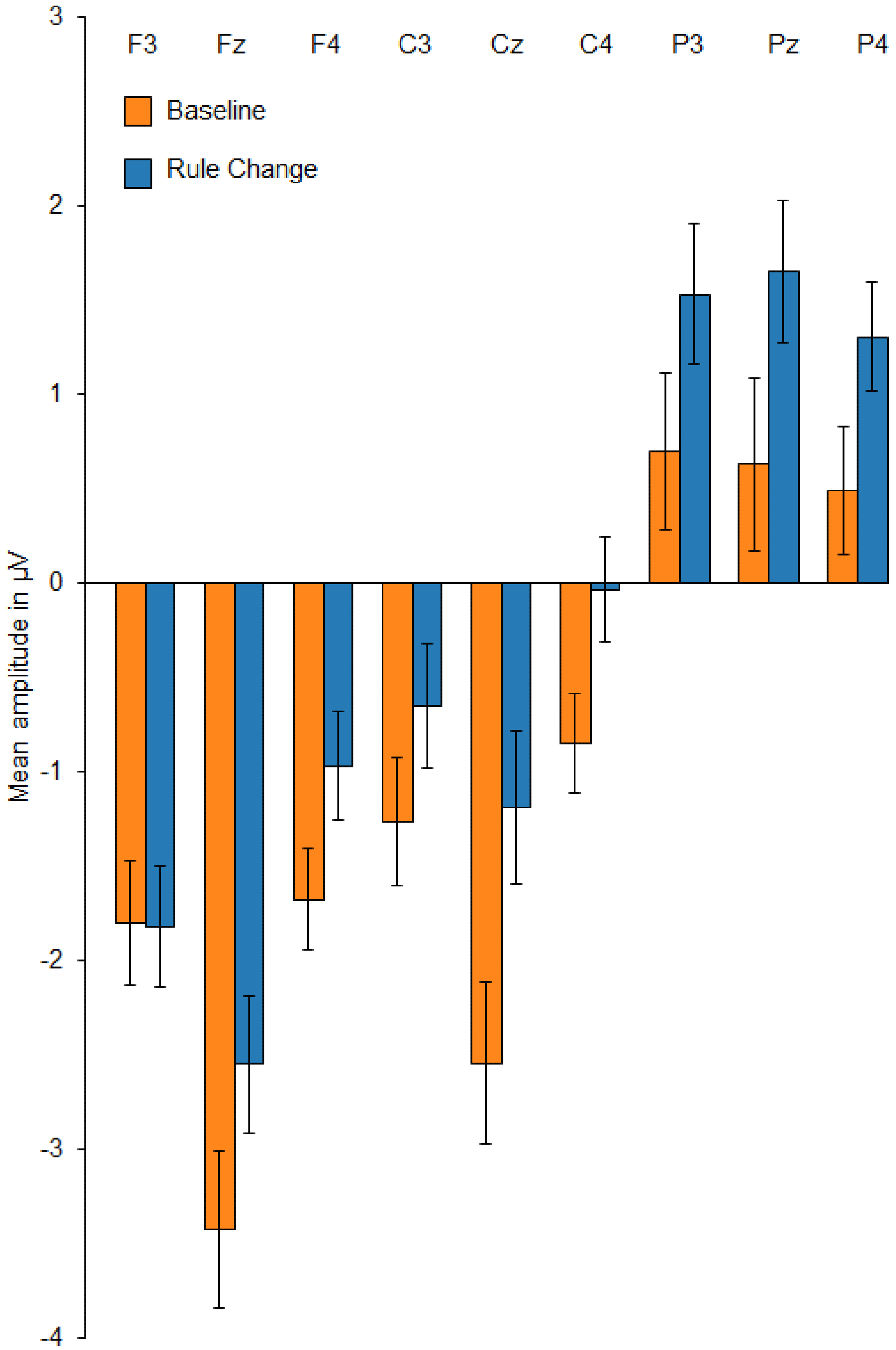


Figure 7-4. Mean amplitudes (300 to 500 ms) of electrodes of interest for stimulus-locked ERPs for critical letter in first position (only followed by correct entries). Error bars indicate standard errors.

Response-locked Analyses (Position 1)

This section includes the response-locked data for critical keys on first position. Additional response-locked data for critical keys in fifth position can be inspected in Appendix 7-C (Table 7-5, Figure 7-7 and Figure 7-8). Three separate ANOVAs were conducted for response-locked mean amplitude, covering the -600 to -400 ms, -400 to -200 ms and -200 to 0 ms pre-response interval. Results of these ANOVAs are summarized in Table 7-2, revealing amongst others significant three-way interactions across all three time intervals. ERP plots and scalp maps are plotted in Figure 7-5, mean amplitudes can be inspected in Figure 7-6.

Table 7-2. Results of the three separate 2 (block: Baseline vs. Rule Change) x 3 (anteriority: frontal vs. central vs. parietal) x 3 (laterality: left, central, right) ANOVA for the three different time windows for response-locked data for critical letter in position 1. Ant = Anteriority, Lat = Laterality.

		-600 to -400 ms				**-400 to -200 ms**				**-200 to 0 ms**			
	df	*F*	*P*	η_p^2	ε	*F*	*p*	η_p^2	ε	*F*	*p*	η_p^2	ε
Block	1, 18	2.158	.159	.107	1.00	4.705	**.044**	.207	1.000	0.120	.733	.007	1.000
Ant	2,36	27.997	**<.001**	.609	.656	21.765	**<.001**	.547	.688	6.230	**.018**	.257	.579
Lat	2, 36	5.689	**.007**	.240	1.00	1.925	.161	.097	1.00	4.643	**.018**	.205	.941
Block* Ant	2, 36	3.692	.060	.170	.623	2.487	.122	.121	.638	5.347	**.016**	.229	.782
Block* Lat	2, 36	3.221	.053	.152	.971	1.525	.231	.078	1.000	3.068	.061	.146	.969
Ant* Lat	4, 72	10.899	**<.001**	.377	.852	9.485	**<.001**	.345	.922	6.259	**<.001**	.258	.957
Block* Ant*Lat	4, 72	3.445	**.019**	.161	.820	5.516	**.002**	.235	.742	7.406	**<.001**	.291	.859

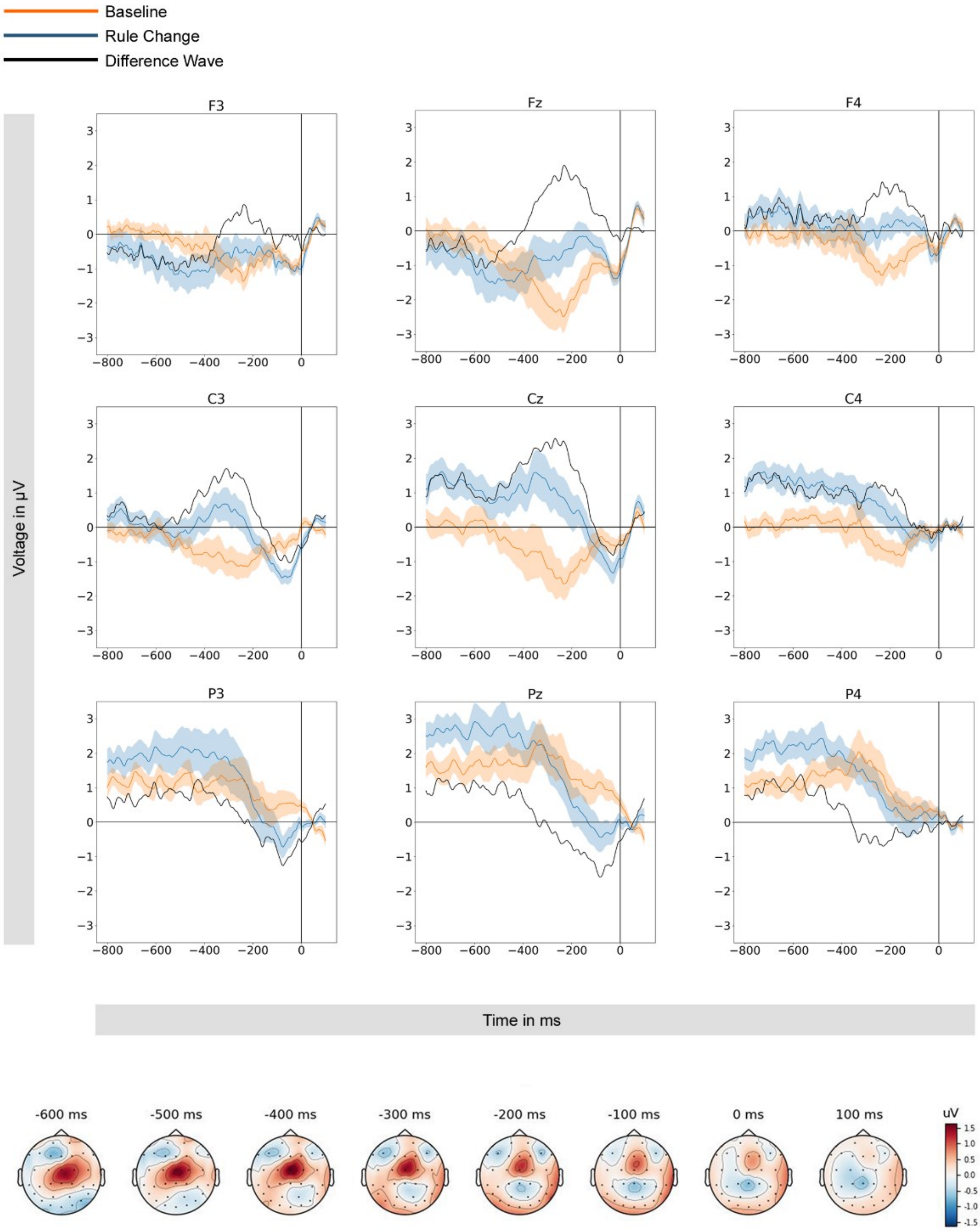
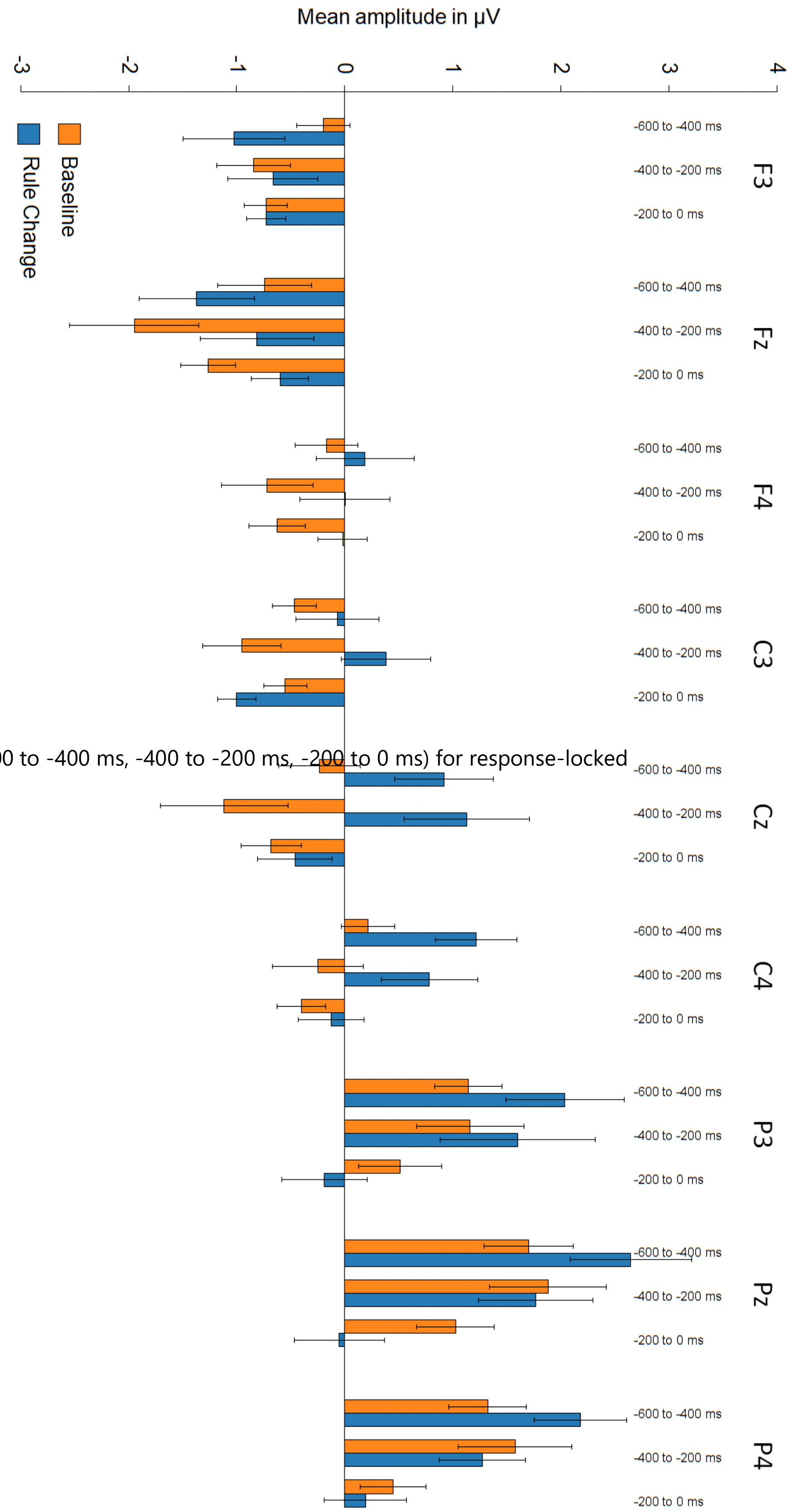


Figure 7-5. Top: Response-locked ERPs (-800 ms to 100 ms) and difference wave for correct keypresses of critical letters in first position. Transparent ribbons indicate standard errors. Bottom: Corresponding scalp distribution of difference wave from -600 ms to 100 ms.



f all three pre-response time intervals (-600 to -400 ms, -400 to -200 ms, -200 to 0 ms) for response-locked
ition. Error bars indicate standard errors.

7.4 DISCUSSION

The aim of the present study was to scrutinize the role of response inhibition for interference control in motor tasks, by examining electrophysiological data (ERPs). To this end, we intentionally induced interference with a letter switch paradigm that was intended to disrupt participants in their highly automatized typing behavior and demand for interference control.

First of all, in line with previous research (Jordan, 1995; Sperl & Cañal-Bruland, 2020b; Sperl, Gergeleit, & Cañal-Bruland, submitted; Yamaguchi & Logan, 2014), behavioral data on typing performance revealed a significant increase in RT and errors for those keys affected by the letter switch compared to non-switched letters. In both critical positions, switched letters led to longer reaction times and more errors. The majority of errors in fact occurred when participants accidentally pressed the key at the original location, hence representing the trials when response inhibition failed and the wrong action could not be stopped in time (cf. Figure 7-2). This replicates findings by Sperl, Gergeleit, and Cañal-Bruland (submitted) and shows that such a type of equipment manipulation (Newell, 1986) can successfully induce interference and generate a considerable response conflict.

With regard to the *stimulus-locked ERPs*, we hypothesized an increased P3 component (a characteristic of response inhibition in (Xie et al., 2017) in successful Rule Change compared to Baseline trials. In fact, in the time window of 300 to 500 ms, more positive mean amplitudes were observed at all three regions of interest (frontal, central and parietal; see Figure 7-4) with a maximal positivity at parietal sites (P3, Pz, P4). First, the observed topography is in line with previous studies which have reported an enhanced P3 component in various inhibition tasks (utilizing stopping paradigms) at central (Greenhouse & Wessel, 2013; Wessel & Aron, 2015), central midline (Greenhouse & Wessel, 2013; Kok et al., 2004), fronto-central (Etchell et al., 2012; Falkenstein et al., 1999) and parietal sites (Xie et al., 2017). As stated in the introduction, the P3 component is known to be elicited by novel, infrequent stimuli (oddballs), changes of stimulus regularity, strategic approaches (Luck, 2014) as well as by stimuli of high significance (Barry et al., 2020), especially those requiring a response (Verleger, 2020), all of which applies to the confrontation with switched letters in our interference paradigm. Second, the maximal positivity at the parietal electrodes accords well with Xie et al. (2017) who also found the P3 component in the response inhibition trials to be especially pronounced in parietal regions and consequently interpreted this component as a P3*b*. Indeed, a more parietal/posterior localization is typical for the P3b (Barry et al., 2020; Squires, Squires & Hillyard, 1975). Whereas the P3a is often reported to reflect attention-related processes, the P3b has been suggested to reflect memory-related and evaluative processes and might further be related to decision and response processes (Hillyard & Kutas, 1983; Verleger, 2020) which are likely to be particularly demanded following the letter switch. Of relevance, Verleger (2020) proposes that the P3b possibly reflects the unexpected *response* rather than the unexpected *stimulus*. This idea appears to be in direct correspondence with the demands posed by our paradigm, since we kept the stimulus constant (unlike, for instance, in oddball paradigms) and just introduced a novel stimulus-response-pairing calling for a different response. Remarkably, the ERPs at the parietal electrodes reveal two positive peaks, one between 250 and 400 ms which was similar in Baseline and Rule Change, and a second one between 400 and 600 ms which was larger in the Rule Change condition (see Figure 7-3). These two peaks may reflect an earlier P3a (which, based on the findings by Xie et al. (2017), should indeed not differ across conditions) and a later P3b which is assumed to differ when comparing response inhibition trials with control trials. This observation is, in fact, in line with the pattern reported by Xie et al. (2017) who found the P3b to be explicitly characteristic for response inhibition, whereas larger posterior N1 and frontal P3a were characteristic for rule inhibition and larger frontal N2 for flanker inhibition. Following these ERP patterns, it seems likely that response inhibition is at play when dealing with interference in motor tasks, whereas other inhibition dimensions (Friedman & Miyake, 2004; Xie et al., 2017) appear to be less involved in the present paradigm.

These findings do not only seem to corroborate the particular relevance of prepotent response inhibition for motor skill change, they also provide further evidence of inhibition representing a multidimensional construct (as we found ERP patterns specific for one type of inhibition) and highlight the necessity to treat it as such (Friedman & Miyake, 2004; Kramer et al., 1994; Xie et al., 2017). Taking these subdimensions into account might therefore be of utmost relevance with regard to cognitive test selection (for both diagnostic as well as research purposes) and evaluation and comparison of empirical findings in terms of research synthesis (Rey-Mermet et al., 2018). However, various approaches to classify the dimensions of inhibition currently exist and there is no golden standard yet (Friedman & Miyake, 2004; Kramer et al., 1994; Nigg, 2000; Xie et al., 2017). Comparing the characteristics of response inhibition with other types of inhibition such as proactive vs. reactive inhibition, one might argue that response inhibition may be more reactive in nature, possibly also comprising inhibitory processes at a motor rather than cognitive level (Harnishfeger, 1995), causing the stopping of a response that is already in progress (Angelini et al., 2016; Meyer & Bucci, 2016). This is indeed different from the act of ignoring irrelevant stimuli (flanker inhibition / resistance to distractor interference) and the suppression of irrelevant memory contents to access working memory (rule (cognitive) inhibition / resistance to proactive interference) which appear to involve more preparatory strategies and may reflect inhibition at more cognitive (and possibly earlier) levels (Di Russo et al., 2016; Friedman & Miyake, 2004; Xie et al., 2017). In our paradigm, such a cognitive inhibition might primarily involve the suppression of the knowledge about the conventional letter-key mapping, which, however, according to our data, seems to be less relevant for interference control in motor tasks. Currently, we can only speculate about the reasons for this inferior role, such as that engaging cognitive inhibition at an earlier level might be too difficult or less functional due to, e.g., limited temporal resources or high task complexity. Hence, interference control in motor tasks may instead occur at a later (motor) level where motor responses are stopped after response conflicts have been detected (Meyer & Bucci, 2016). This is interesting regarding the fact that in our paradigm (contrary to stop signal paradigms) there is no genuine stop signal which pops up unexpectedly, but a rule which is present before the task execution (Angelini et al., 2016; Aron, 2011) (unless spotting the critical letter was processed as some sort of a stop signal). Whereas the question to what extent reactive inhibition might be covered by the concepts of prepotent response inhibition and how the reported subdimensions of inhibition might reflect cognitive versus motor inhibition exceeds the scope of this paper, the present observations call for future research addressing the electrophysiological patterns associated with inhibition dimensions more generally (for initial steps, see Brydges et al., 2012; Vuillier et al., 2016; Xie et al., 2017).

While these stimulus-locked ERP speak in favor of an involvement of prepotent response inhibition, in contrast to previous work (Sperl & Cañal-Bruland, 2020b; Sperl, Gergeleit, & Cañal-Bruland, submitted), in the present study, we did not observe a significant relationship between the scores from the Stop-Signal Task and the amount of performance deterioration. Neither was the difference in amplitude of the P3 associated with this test score. A series of studies examined ERPs directly related to stopping tasks (Huster et al., 2013). While these studies often compare successful and unsuccessful stop trials and observe differences in N2/P3 latencies and topography (Kok et al., 2004; Wessel & Aron, 2015), they leave much room for future research to investigate how the general ability of inhibition measured by these tests modulates the P3 amplitude in successful interference control trials. The fact that the previously observed relationship between inhibition test score and the extent of performance deterioration did not replicate in this study could also – at least partially – reside in a lower sample size compared to previous studies (Sperl & Cañal-Bruland, 2020b; Sperl, Gergeleit, & Cañal-Bruland, submitted)[9]. While these earlier studies were explicitly designed to investigate such a relationship, sample size in the current study was computed via power analysis in primary interest of the ERP effects.

As far as the later interval of the stimulus-locked ERPs is concerned, both conditions elicited slow parietal negative potentials, partially varying in latency in accordance with processing time (and response onset) delays in the Rule Change condition (see Figure 7-3). This component may reflect a late posterior negativity (LPN), a component which has been observed to occur before or around a response. It has been proposed to represent enhanced action monitoring caused by response conflict as well as the recapitulation of study details at test (Wolk et al., 2007; for a review, Johansson & Mecklinger, 2003). Both processes are likely to occur in our task as the letter switch causes a response conflict, and responding to critical letters requires a retrieval of the new block-specific task instructions (letter switch). However, note that the LPN was not at the main focus of the present study and should be interpreted with caution because its measurement may be affected by latency variability of the first keystrokes (see horizontal bars in Figure 7-3), thus potentially containing motor-related potentials (Scaltritti et al., 2018).

Regarding the *response-locked data*, it is important to note that we analyzed these in an exploratory manner. We split the pre-response interval into three 200 ms intervals and found significant three-way interactions for almost every interval. Generally speaking, when a critical key occurred in the first position, this was accompanied by more positive amplitudes in the Rule Change condition in central and parietal sites which, however, continuously decreased and inverted into negativity around 200 ms before the critical keystroke (see Figure 7-5). On the one hand, this negative deflection could involve the previously discussed late negativity

[9] For additional interest: The non-significant correlation between error difference for critical letters in first position and SSRT (r = .115, p = .640) is still within the confidence interval of a similar correlation between SSRT and error difference for critical letters (r = .307, p = .048, CI: .003 ≤ r ≤ .559) observed in an earlier study (Sperl et al., submitted). This might support the assumption that statistical power was simply not sufficient to test for this association. To repeat, in contrast to earlier studies, the association between SSRT and performance deterioration was not the main focus of the current study, which was designed for investigation of the reported ERP effects (see also power analysis in section 7.2).

before and around the response (Johansson & Mecklinger, 2003). On the other hand, such a negative-going voltage deflection right before a voluntary, self-paced movement is often observed as a Bereitschaftspotential (BP), thereby possibly (also) representing some kind of movement preparation in the present paradigm (Deecke & Kornhuber, 2003; Jahanshahi & Hallett, 2003). We suggest that the larger amplitude of this pre-response negativity for the rule change than baseline condition (Figure 7-5) reflects a greater effort in motor control as automaticity is disrupted. This interpretation would be consistent with a study by Sommer and Leuthold (1994), who found that the amplitude of the BP in the 200 ms before the response increased in two conditions that required a greater degree of motor control (increasing peak response force and delaying time to motor peak force after an imperative stimulus). The major challenge in interpreting these findings consists of the fact that, in general, few response-locked analyses have been conducted in the context of response inhibition so far. Indeed, most of the ERP analyses addressing the cognitive process of response inhibition are stimulus-locked (Dimoska et al., 2006; Etchell et al., 2012; Greenhouse & Wessel, 2013; Kok et al., 2004; Wessel & Aron, 2015; Xie et al., 2017) whereas response-locked analyses were mainly intended to look at the post-response interval (e.g., Falkenstein et al., 1999; Ramautar et al., 2006). The few existing studies investigating ERPs associated with the motor skill of typing, in turn, computed mainly LRPs (lateralized readiness potentials) (Logan et al., 2011; Pinet et al., 2015; Scaltritti et al., 2017; Scaltritti et al., 2018). Only Scaltritti et al. (2018) visually inspected typing-induced response-locked ERPs and seemed to observe a similar course (slightly negative going) for the control trials (constraintless typing) to our study. Further research on response-locked ERPs derived from complex movement sequences is needed to disentangle the different sources that might contribute to this ERP course. Even if such research would benefit from novel analysis methods to account for latency variability in single trials (e.g., Ouyang et al., 2011), the methodological challenges when dealing with sequences of multiple complex movements should not be underestimated.

Due to the novelty of the present paradigm and with regard to future research, we would like to share some further methodological considerations. One of the key challenges in typing studies are posed by eye and head movements that occur when switching attention from the monitor to hands and keyboards. As these are known to cause large movement artifacts and decrease signal-to-noise ratio, previous study designs were often forced to prohibit visual attention towards hands and keyboard or include only participants that are able to blind-type

(Pinet et al., 2016; Pinet et al., 2019; Scaltritti et al., 2018). Beside the fact that even skilled typists happen to get their fingers out of place on the keyboard, an increased need for visual control is inherent in our interference paradigm (Sperl & Cañal-Bruland, 2020b; Sperl, Gergeleit, & Cañal-Bruland, submitted). With a novel set-up, namely the installation of a small external monitor above the keyboard (see Figure 7-1), we could substantially reduce eye movements to a minimum by still allowing participants to monitor their hands which enabled us to assess a more natural typing behavior. Indeed, the effectiveness of this innovative study set-up that, to our knowledge, has not been implemented elsewhere thus far, was visible in both the quality of the present EEG data and in the small proportion of ocular or motor artifacts we encountered.

Further, to assess prepotent response inhibition we administered the classic Stop-Signal Task following Verbruggen et al. (2008). However, test selection here offers a range of alternatives as many variations of stop paradigms as well as alternative task families (e.g., Go/NoGo tasks) exist which might also be considered appropriate methods to measure response inhibition (for a review, see e.g., Huster et al., 2013). Though the reported *stop-change tasks* very likely still include the same inhibitory mechanisms and might be seen as an extension of stopping tasks (Boecker et al., 2013), a differentiation between stop and stop-change tasks might indeed be of crucial relevance, at least for ERP research as they are reported to produce different electrophysiological patterns (Krämer et al., 2011). In fact, we detected an ERP pattern similar to the one Krämer et al. (2011) observed for a stop-change tasks (enhanced P3) which differed from the one for stop tasks (enhanced N2 and P3). Moreover, the task in our paradigm as well as a motor skill change in real life is likely to reflect a change rather than a pure stopping process. As we were interested in the specific role of response inhibition, we chose one of the gold standard paradigms for assessment. However, future research might also consider involving stop-change tasks for cognitive testing (Boecker et al., 2013).

Regarding the stimulus-locked approach, the peculiarity might be mentioned that the onset was strictly speaking not only the onset of the first letter. Instead, the whole word appeared at once, which limited the stimulus-locked analyses to the words that contained the critical letter in first position. This procedure was essential to generate typing flow because individuals usually look a few letters ahead which indeed is a beneficial strategy, especially for fast typing (Yamaguchi, 2019). So, word components beyond the first letter were likely to be perceived and processed. Nevertheless, we observed remarkable differences in the stimulus-locked ERPs when the properties of the first letter were changed. Further limitations regarding both stimulus- and response-locked analyses in typing studies often reside in the contamination with previous and subsequent events (keystrokes or stimulus onset). Moreover, the selection of an adequate baseline can often turn out complicated for response-locked analyses (Luck, 2014) and needs to be considered carefully, also with regard to this contamination (for discussion and alternative approaches, see, e.g., Alday, 2019; Lopez-Calderon & Luck, 2014; Luck, 2014). Despite the challenges associated with response-locked approaches, we believe that especially when investigating motor actions and complex behavior, it is vital and insightful to include response-related methods regarding both the pre- (Pinet et al., 2015) and post-response interval (Ramautar et al., 2006).

While exceeding the scope of this study, a series of approaches might also be interesting for future research regarding motor skill change tasks. For example, the present paradigm could be easily adapted towards a paradigm to assess the lateralized readiness potential (Coles, 1989; Eder et al., 2012; Logan et al., 2011; Pinet et al., 2015; Scaltritti et al., 2018), and this would allow researchers to quantify covert response activation of prepotent responses during various stages of motor relearning. Additional latency analyses could provide further insight into the time-course of inhibitory processes (Wessel & Aron, 2015). In this context, it would be interesting to modify the present design insofar that ERPs between successful and unsuccessful trials of interference control can be compared (Greenhouse & Wessel, 2013; Kok et al., 2004; Ramautar et al., 2006). Finally, also the investigation of interindividual differences in the ERP following individual characteristics (such as, e.g., general inhibitory abilities) might provide further insights into the mechanisms involved in interference control in motor tasks (Sperl & Cañal-Bruland, 2020b).

To conclude, this study presented one of the first experimental attempts to investigate the electrophysiological correlates of motor skill change. Specifically, the interest was on the question which inhibitory mechanisms might be at play when dealing with interference that arises from strong pre-existing behavioral action tendencies. Most importantly, disrupting participants in their automatism and inducing proactive interference led to larger P3 amplitudes after rule change. This was visible at frontal, central and most pronouncedly at parietal sites, which strongly resembles the ERP pattern commonly reported for response inhibition (Huster et al., 2013; Kok et al., 2004; Krämer et al., 2011; Wessel & Aron, 2015; Xie et al., 2017). Building on previous research (Krämer et al., 2011; Sperl & Cañal-Bruland, 2020b; Sperl, Gergeleit, & Cañal-Bruland, submitted; Xie et al., 2017), the present findings support the suggested role of prepotent response inhibition for successful interference control in motor tasks at an electrophysiological level. Thereby, this study was able to give first insights into the ERPs associated with interference control in motor tasks. While this work could provide only initial steps and findings, there is much room for future research to investigate neurophysiological correlates of motor skill changes.

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APPENDIX

APPENDIX 7-A

Table 7-3. Stimulus lists of to-be-typed words in Baseline and Rule Change.

critical letter [S]/[L]					
position 1		position 5		none	
suche	lampe	kannst	total	wörter	kaufen
suppe	liebe	bremsen	behelfen	baum	gut
sand	laub	genesung	banal	rad	nie
sehen	liegen	grausam	apfel	tür	raum
sprache	lahm	kreis	ideal	kaum	mann
sucht	linde	peitsche	bemalen	fahren	montag
schicken	licht	phrase	bettler	tee	neu
schuh	lügen	wachsen	gabel	hindern	oben
sau	lachen	chaos	zuhalten	mehr	hinab
sache	lauern	chips	fabel	und	tag
sonne	lippe	jedes	beeilen	bahn	tier
super	leicht	neues	erdulden	merken	mittag
saft	leider	famos	kegel	bin	gern
saat	labor	dachs	areal	hund	drei
saugen	landen	artist	ampel	grün	grenze
sauber	lang	brause	kugel	rot	grafik
schaden	latent	büchse	nagel	ja	hahn
stehen	laterne	getöse	royal	nein	parken
schacht	laufen	krebse	zügel	puma	kino
schaffen	leben	attest	pfeil	grau	regen
schein	lehnen	indisch	finale	hoch	papier
ski	leer	abwasch	erdöl	bach	gruppe
schiff	lehren	ethisch	abmalen	kuchen	weiter
schmerz	lied	fuchs	april	park	wundern
schnecke	lupe	irdisch	mobil	backen	kante
sagen	leute	achtsam	gehilfe	trocken	gegen
sitzen	locker	wirksam	nudeln	bitten	boden
strafe	loch	wachsam	komplex	mauer	womit
strecke	luft	biegsam	erfolgen	benutzen	gerade
singen	lunge	dreist	gehalt	gehen	keine
sage	leiter	abwesend	abholen	finden	noch
seife	lagern	dienstag	abmelden	hoffen	jetzt
skript	loben	egoist	ärmel	kommen	immer
sogar	lohnen	hohes	bauplan	warum	mich
sparen	lenken	minus	bewölkt	reden	wir
schatz	leihen	bares	echolot	zeigen	ohne
sporn	linear	fransen	fachlich	tanzen	von
spotten	legende	herbst	gemalt	auto	danken
stau	leib	jüngst	gepflegt	brief	bekommen
stark	laut	quatsch	überlegt	dürfen	feiern

APPENDIX 7-B

Table 7-4. Correlation matrix of inhibition test and interference parameters. Uncorrected values are reported.

Variable (Test)	Parameter		Flanker Effect	SSRT	$PI_{List\ 2}$	$PI_{List\ 3}$	Int_{RT} (Pos. 1)	Int_{RT} (Pos. 5)	Int_{Error} (Pos. 1)	Int_{Error} (Pos. 5)	$P3_{diff\ Cz}$
Resistance to Distractor Interference (Eriksen-Flanker Task)	Flanker Effect	***r***	—								
		p	—								
Prepotent Response Inhibition (Stop-Signal Task)	SSRT	***r***	**-.111**	—							
		p	.623	—							
Resistance to Proactive Interference (Brown-Peterson Variant)	$PI_{List\ 2}$	***r***	**.163**	**-.177**	—						
		p	.470	.431	—						
	$PI_{List\ 3}$	***r***	**.117**	**.011**	**-.025**	—					
		p	.604	.960	.913	—					
Interference (RT) (RT difference critical letters Rule Change vs. Baseline)	Int_{RT} (Pos. 1)	***r***	**.115**	**.052**	**.127**	**.022**	—				
		p	.639	.832	.605	.927	—				
	Int_{RT} (Pos. 5)	***r***	**.333**	**-.039**	**.210**	**.348**	**.710**	—			
		p	.163	.875	.387	.144	$< .001$	—			
Interference (Errors) (Error difference critical letters Rule Change vs. Baseline)	Int_{Error} (Pos. 1)	***r***	**.169**	**.115**	**-.047**	**.032**	**.463**	**.535**	—		
		p	.490	.640	.848	.898	.046	.018	—		
	Int_{Error} (Pos. 5)	***r***	**.032**	**.041**	**-.012**	**.291**	**.176**	**.278**	**.519**	—	
		p	.895	.867	.960	.228	.471	.250	.023	—	
P3 amplitude $difference_{max}$	$P3_{Diff\ Cz}$	***r***	**.115**	**.370**	**.036**	**.059**	**.201**	**.082**	**.280**	**.286**	—
		p	.639	.119	.885	.810	.409	.737	.246	.236	—

APPENDIX 7-C

Response-locked analyses for critical letter in position 5

Table 7-5. Results of the three separate 2 (block: Baseline vs. Rule Change) x 3 (anteriority: frontal vs. central vs. parietal) x 3 (laterality: left, central, right) ANOVA for the three different time windows for response-locked data for critical letter in position 5. Ant = Anteriority, Lat = Laterality.

		-600 to -400 ms				**-400 to -200 ms**				**-200 to 0 ms**			
	df	*F*	*P*	η_p^2	ε	*F*	*p*	η_p^2	ε	*F*	*p*	η_p^2	ε
Block	1, 18	2.481	.133	.121	1.000	1.167	0.294	0.061	1.000	1.362	0.258	0.070	1.000
Ant	2,36	11.911	**< .001**	.398	.850	4.561	**0.032**	0.202	.681	2.710	0.081	0.131	.985
Lat	2, 36	7.417	**.002**	.292	1.000	3.458	**0.049**	0.161	.880	2.610	0.087	0.127	1.000
Block* Ant	2, 36	0.616	.473	.033	.615	0.004	0.980	0.000	.664	0.696	0.452	0.037	.665
Block* Lat	2, 36	5.774	**.007**	.243	1.000	9.199	**< .001**	0.338	1.000	0.277	0.760	0.015	1.000
Ant* Lat	4, 72	1.034	.395	.054	.982	1.437	0.241	0.074	.767	1.514	0.209	0.078	.970
Block* Ant*Lat	4, 72	6.015	**.001**	.250	.748	2.684	0.051	0.130	.813	2.394	0.086	0.117	.668

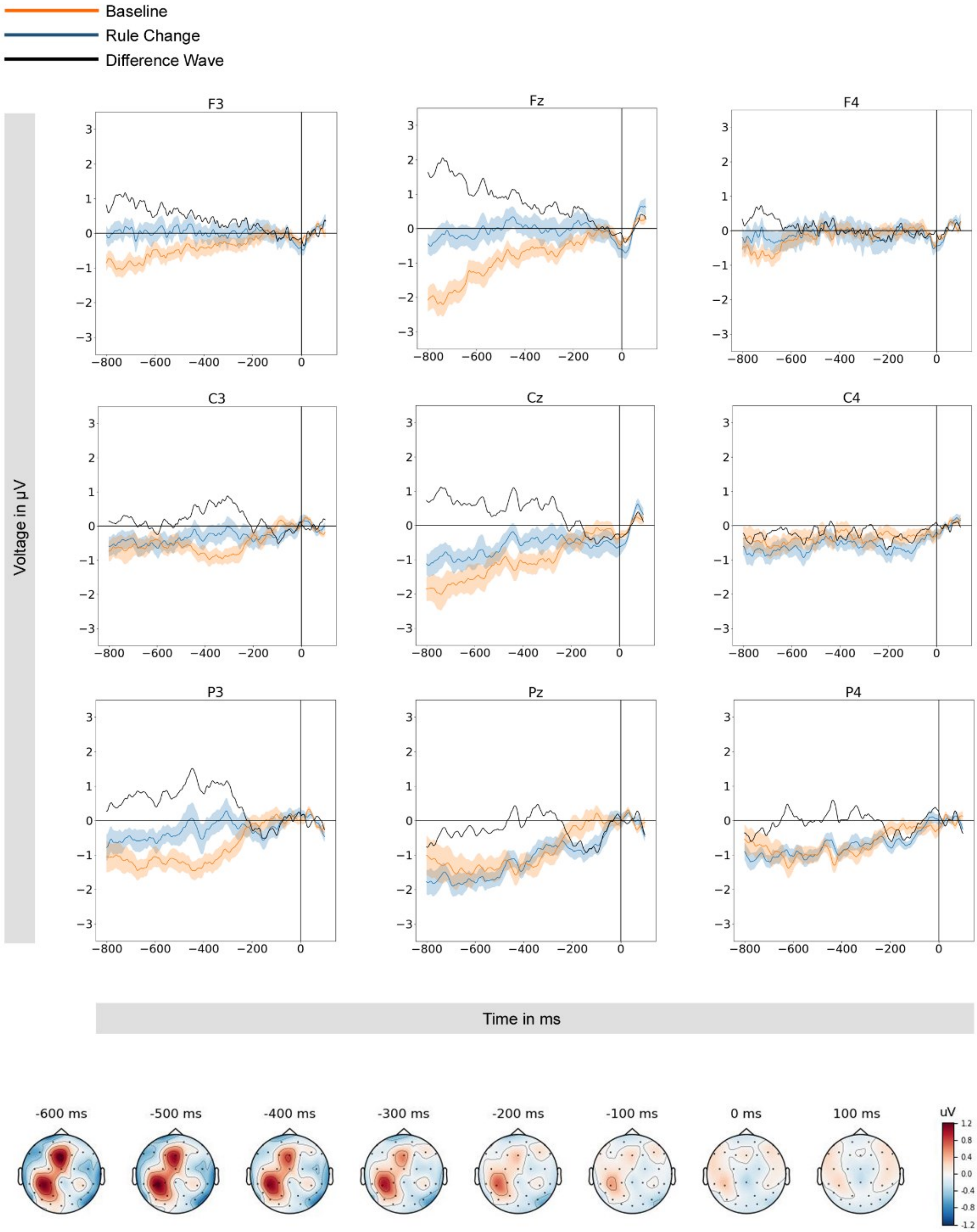
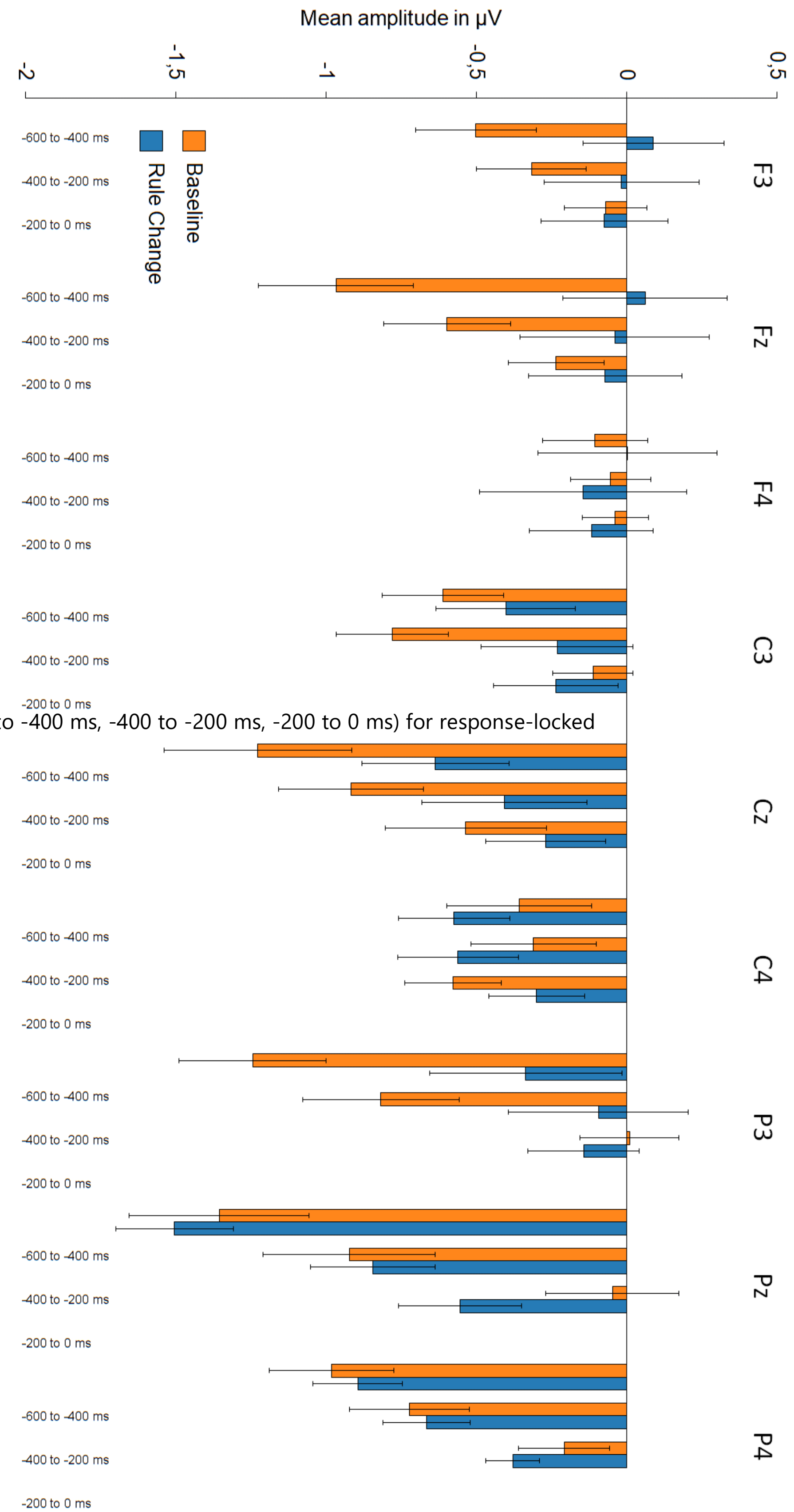


Figure 7-7. Top: Response-locked ERPs (-800 ms to 100 ms) and difference wave for correct keypresses of critical letters in fifth position. Transparent ribbons indicate standard errors. Bottom: Corresponding scalp distribution of difference wave from -600 ms to 100 ms.



hree pre-response time intervals (-600 to -400 ms, -400 to -200 ms, -200 to 0 ms) for response-locked
Error bars indicate standard errors.

CHAPTER 8

GENERAL DISCUSSION

8.1 THEORETICAL DISCUSSION

8.2 METHODOLOGICAL CONSIDERATIONS

8.3 FUTURE DIRECTIONS & OUTLOOK

8 GENERAL DISCUSSION

8.1 THEORETICAL DISCUSSION

The central aim of the current dissertation project was to scrutinize some of the mechanisms underlying the process of motor skill change. This endeavor was driven by the challenges that often go along with motor skill change in practice (Carson & Collins, 2016; Panzer, 2002) and the scarcity of present research regarding this topic (Carson & Collins, 2011). While often being fueled by the intention to raise the performance level, skill modifications have frequently been reported to be associated with proactive interference effects, especially when the pre-existing behavior is strongly automatized (Panzer, 2002; Pöhlmann, 1994; Radvansky, 2017; Weigelt et al., 2020). Consequently, performers often experience initial performance decrements (Carson & Collins, 2011; Panzer, 2002). In practice, the existence of such performance decrements even deters performers, e.g. athletes, from voluntarily changing to a technique that would actually allow for a better performance, as especially professionals cannot afford a diminished performance level over a longer period of time (Oreg, 2003). Thus, the research aim emerged to investigate not only costs in motor skill change per se, but also a series of potential factors which might determine the extent of these performance decrements (see Chapters 2.2 and 2.3). Specifically, by identifying critical factors influencing the amount of proactive interference in a skill change task, such as action constraints, inhibitory functions, age and proficiency, the present research may not only contribute to a better understanding of motor skill change. In the future, such knowledge may even aid to accelerate various types of change processes and enable performers to profit sooner from potential benefits of the skill change.

8.1.1 PROACTIVE INTERFERENCE IN MOTOR SKILL CHANGE TASKS

First and foremost, all four empirical experiments (Chapters 4 to 7) showed that proactive interference effects in motor skill change tasks, here assessed via the complex motor skill of typing (Yamaguchi, 2019), do indeed exist (cf. Mühlbauer et al., 2007; Panzer, 2002). In each of the four studies, participants encountered a task manipulation which disrupted their well-established automatized motor behavior resulting in strong and immediate performance decrements (Yamaguchi & Logan, 2014). In fact, it was observable how pre-existing automatisms triggered the participants to execute the familiar behavior – such as using the left index finger (see Chapters 4 and 5) or pressing a key at the original location (see Chapters 6 and 7) – and resulted in difficulties to implement the new task instructions. This, in turn, led to strong overall performance decrements, which within this typing paradigm were manifested in both performance parameters: typing times and errors (Chapters 4, 5, 6 and 7). Importantly, the transfer test in Chapter 4 as well as the data on IKSI (Chapters 5, 6 and 7) corroborated that this performance decline was indeed driven by the concrete rule change manipulation instead of representing an artifact of a novel task situation in general. Moreover, interference was evoked by both types of rule changes, i.e. the finger prohibition (see Chapters 4 and 5) and the key switch (see Chapters 6 and 7) as well as by both types of stimulus material used, i.e. continuous text (Chapters 4, 5 and 6) and separated unrelated words (Chapter 7). This observation is in line with and extends earlier research which found typing performance to deteriorate when letters typed by certain fingers had to be omitted (Snyder & Logan, 2013) or when keys were switched in their location (Gordon et al., 1994; Jordan, 1995; Parasher et al., 2001; Yamaguchi et al., 2013). Furthermore, both manipulations had a significant impact on subjective (Chapter 6) and objective (Chapter 5) visual strategies, resulting in increased visual attention to hands and keyboard after rule change. To draw an interim conclusion, the experimental findings consistently demonstrate that, at least on a short time scale, proactive interference and the associated performance decrements are indeed present in motor skill change tasks when an automatized motor behavior like in the typing task is addressed.

8.1.2 ACTION CONSTRAINTS

The studies presented in Chapter 4 and 5 investigated the effectiveness of motor restrictions for successful rule change implementation. As described in detail in Chapter 2.2, the underlying idea for this approach was that detrimental proactive interference from a pre-existing skill might be reduced if the undesired old motor behavior cannot be executed anymore. Specifically, such a motor restriction was intended to reduce degrees of freedom and the automatic tendency to execute an irrelevant, but still dominant movement option (cf. Bernstein, 1967). Furthermore, it was presumed to save crucial time resources, since undesired movements are immediately physically stopped the moment they become initiated (see also techniques of motor guidance, e.g., Kümmel et al., 2014). In Chapter 2.2, we argued that an integration of such a motor restriction for interference reduction is indeed unique and exclusive for interference situations addressing *motor* skills, since certain response options can be physically precluded which is not or less possible in memory interference paradigms such as word list paradigms where a verbal response is given (e.g., Kane & Engle, 2000; Rosen & Engle, 1998). In this context, we introduced a series of examples that already exist in the applied field where such motor restrictions are already used to correct wrong or suboptimal motor behavior (e.g., Bettany-Saltikov et al., 2008; Buchhorn & Ziai, 2009; Cho et al., 2015; Cotterman et al., 2005; Dicks & Chow, 2010; Duda, 1988; Klausner, 2018; Zhang et al., 2016). However, past research has rarely addressed this technique from a scientific point of view (for exceptions, see Davids et al., 2008; Gray, 2018).

To assess the effectiveness of such a motor restriction, the critical manipulation in the studies presented in Chapters 4 and 5 involved the new rule that the left index finger could not be used for further typing. The respective motor restriction, which was intended to facilitate this rule change implementation, consisted of a finger bandage which prevented the left index finger from moving (see Figure 4-1 and Figure 5-1). The results regarding the effectiveness of this intervention were not conclusive. The first study found the application of a motor restriction to be equally effective as verbal instructions (see Chapter 4). We reason that even if the motor restriction does not seem to be superior to verbal instructions alone, it might nonetheless bear a benefit, such as in case of reduced cognitive control capacities (following e.g., dual tasks, divided attention, temporarily increased cognitive load, mental disabilities or poorer cognitive functioning in general). In fact, in the field of sports it might thus turn out to be a useful tool regarding the acquisition or training of complex sport-specific motor sequences or game situations which offer limited cognitive resources (Carson et al., 2020; Furley et al., 2013; Jones & Hardy, 1989). In our second study, some of the analyses revealed the presence of the bandage (which was included as a factor in each regression model) to be a significant predictor of the amount of performance decrements, whereas other analyses did not (Chapter 5). Hence, while the first study revealed the motor restriction to be as effective as verbal instructions alone, this was different in the second study which at least partially indicated a benefit of the motor restriction. It also needs to be stressed that the effects found in this investigation only denote effectiveness on a short-term level. Assuming that a motor restriction may lead to immediate performance benefits, the question that remains to be answered is what happens after an intervention, i.e. when the motor restriction is withdrawn again. This is relevant to consider since, while some action constraints are possible to last during and even beyond practice (such as exercising using a Smith Machine or wearing a support wrist in Bowling; Cotterman et al., 2005; Duda, 1988), others are inherently intended to last only temporarily during training phases (such as obstacles for jump height improvement or back corsets; see Chapter 2.2; American Sport Education Program, 2008; Carrozza et al., 2019; Klausner, 2018).

Interestingly, participants came up with different ways to deal with the rule change and generated different solutions on how to replace the left index finger (e.g., with the middle finger or the right index finger) and resist the tendency to keep using it (e.g., by abducting the finger far from the keyboard). Hence, some kind of self-organization seemed to occur, as claimed by the CLA approach (Davids et al., 2008), which, however, following this type of restriction was obviously quite limited. To repeat, the original intention of our manipulation was not to create maximal range for self-exploration as intended by the CLA, but to promote a specific desired movement technique by ruling out a dominant, but undesired alternative (like replacing an Old Way by a New Way, see also Baxter et al., 2004). It would be interesting for future research to further combine the ideas of self-exploration and motor restriction to support performers to generate their own solution in order to deal with specific undesired movement components (Davids et al., 2008; Gray, 2018; Lee et al., 2014). Apart from this, also from a physiological point of view, self-organization might play an important role, as long-term changes, such as the correction of suboptimal postures, often also involve a physiological change and adaptation, such as the building of relevant muscle structures. In such a context, the constant use of a restriction might also turn out detrimental in the long run.

Another aspect worth considering is that in addition to physically ruling out an undesired movement option, a motor restriction might also work as a visual and sensory reminder (since performers immediately receive haptic feedback when they are trying to initiate a restricted movement; Sigrist et al., 2013), which might, additionally, cognitively facilitate the avoidance of the restricted body part. Within the context of mirror neuron systems, it would be conceivable that an observation of a restriction might already have effects on the performer (Liepelt et al., 2009).

To sum up, as stated in the introduction, there are various examples where motor restrictions are already used in the area of sports (e.g., Cotterman et al., 2005; Davids et al., 2008; Duda, 1988), ergonomics (e.g., Bettany-Saltikov et al., 2008; Cho et al., 2015; Klausner, 2018) or rehabilitation (e.g., Buchhorn & Ziai, 2009; Mayer & Siems, 2019) and they apparently prove to be beneficial. The present research provided a first attempt at investigating the cognitive and motor gains of a motor restriction for interference control within an empirical approach and found initial, yet not conclusive, results that point towards a potential profit (see Chapter 5). While this already appears promising in regard to several practical applications (see Chapter 2.2), future research is required to systematically investigate motor restrictions as well as the scope of their potential usefulness.

8.1.3 INTERINDIVIDUAL DIFFERENCES

Notably, within our typing paradigm, we did not only observe a strong increase in mean typing times and errors, but also an enormous increase regarding the standard deviations after rule change (see, e.g., Chapter 7). This observation confirms that participants within the same experimental task experience interference to different extents. Several researchers have proposed that a concept like individual *proneness* (e.g., May et al., 1999) or *susceptibility to interference* (e.g., Bowles & Salthouse, 2003; Earles et al., 1997; Hedden & Yoon, 2006) exists. Consequently, we posed the question which individual factors might account for these interindividual differences regarding interference. In Chapter 2.3, we introduced three potential candidates, namely executive functions, age and proficiency regarding the motor skill, which we assessed (in a primarily exploratory manner) within our empirical studies.

Executive functions

Regarding executive functions, we assumed that cognitive abilities regarding all three common core functions, i.e. working memory, cognitive flexibility and inhibition (Diamond, 2013; Miyake & Friedman, 2012) might be beneficial for successful motor skill change (see Chapter 2.3 for an extensive reasoning). Although working memory and cognitive flexibility showed no association with the amount of interference in the typing task, this was different for inhibition. As inhibition has been suggested to represent a multidimensional construct (Friedman & Miyake, 2004; Kramer et al., 1994; Nigg, 2000; Rey-Mermet et al., 2018) we assessed two (Chapter 5) and three (Chapter 6 and 7) subdimension of this cognitive function, namely resistance to distractor interference, resistance to proactive interference and prepotent response inhibition (Friedman & Miyake, 2004). The most striking observation was that out of all assessed executive functions, mainly prepotent response inhibition revealed an association with the amount of interference in the motor skill change task (see Chapter 5 and 6). That means especially those participants who have poorer prepotent response inhibition abilities (and thereby possibly less efficient action control strategies) suffer most from the rule change. Surprisingly, resistance to proactive interference was not associated with the amount of interference (see Chapter 5 and 6). These results not only speak for inhibition representing a multidimensional construct (Friedman & Miyake, 2004), they also highlight the particular role of prepotent response inhibition in motor skill change. Even if more research is definitely required to clarify the overlap of these concepts, these findings might indicate that inhibition in our motor task occurs more at a motor, and possibly reactive level (Aron, 2011; Chiappe et al., 2000; Harnishfeger, 1995; Lavallee et al., 2014; Meyer & Bucci, 2016), by stopping a process that is already in progress (Meyer & Bucci), rather than in a preparatory way.

Initially, this finding was somewhat surprising, as we originally expected that both the ability to resist irrelevant memory contents (about the original motor behavior) and the ability to suppress undesired, but automatic response tendencies (still using the left index finger or pressing a key at the original location) would be necessary strategies to deal with the new rule in the experimental task. In fact, a prepotent response may indeed also derive from prepotent memory contents (see also *response-override situations* in Levy & Anderson, 2002). However, at least in motor tasks with interference arising from a procedural, stimulus-unspecific source, resisting irrelevant memory contents seems to play an inferior role in interference control (see data in Chapter 5 and 6). This might be different for motor tasks addressing concrete motor sequences, such as sport-specific movement sequences, which partially also demand declarative knowledge (for a more detailed reasoning regarding declarative vs. procedural sources of interference, see Chapter 6).

Moreover, the suggested relevant role of prepotent response inhibition for interference control could be considered in line with a potential advantage provided by motor restriction (cf. Chapter 8.1.2). If the main challenge in such a motor skill change task indeed consists in suppressing strong automatic action tendencies towards the previous behavior, a motor restriction, addressing exactly this component of inhibition might function as an adequate inhibition support (cf. Chiappe et al., 2000).

To further investigate this particular relevance of prepotent response inhibition and go beyond correlative and regressive approaches regarding inhibition as a general ability (cf. Chapter 2.3), in a last step we extended our methodology by conducting a complex electrophysiological experiment. In this study, we assessed the event-related potentials associated with interference control in motor tasks (Chapter 7). Moreover, this methodological approach offered us the possibility to gain further insights on how inhibition as a cognitive process (see Chapter 2.3, Figure 2-5) is involved in situations requiring interference control. To our knowledge, this study is the first of its kind examining brain potentials associated with motor skill change. Since different inhibitory functions have been reported to be characterized by distinct ERP patterns (Xie et al., 2017), this approach appeared promising to examine which inhibition subdimensions might be at play directly in the moment of interference control. Specifically, building on our results from Chapter 5 and 6, we expected the response inhibition subdimension to be engaged in our motor task. Based on previous ERP research (Kok et al., 2004; Krämer et al., 2011; Xie et al., 2017) we hypothesized a more pronounced P3 component in trials requiring interference control compared to control trials. As predicted, we observed ERP patterns previously shown to represent response inhibition in these trials, characterized by larger P3 components (Krämer et al., 2011; Xie et al., 2017). Thereby, the results are in line with previous findings from the behavioral data, corroborating the particular involvement of response inhibition in motor skill change tasks (for detailed results and discussion, refer to Chapter 7).

To conclude, in the empirical studies presented in this thesis, among all five assessed executive functions, the ability to inhibit automatic response tendencies (Friedman & Miyake, 2004) appears to be of particular relevance for successful interference control in motor change tasks. Our work does not only underline the necessity to treat and assess inhibition as a multidimensional construct (Friedman & Miyake, 2004; Kramer et al., 1994; Nigg, 2000; Rey-Mermet et al., 2018; Xie et al., 2017), it also demonstrates how different inhibition subdimensions relate to motor skill change.

Age

We also observed that the interference effects were larger with increasing age, as was shown by the highly significant effects presented in Chapter 5. This observation raises the question whether this relationship is mediated by the dynamics of cognitive functions which are known to decrease with age (Bialystok & Craik, 2006; Wiebe & Karbach, 2018; Zelazo et al., 2004). Especially inhibitory abilities are often reported to deteriorate in later life (Adólfsdóttir et al., 2017; Bialystok & Craik, 2006) and some perspectives even postulate deficits in inhibition to cause the general age-related decline in older adults (Hasher & Zacks, 1988; May et al., 1999). In their meta-analysis, Rey-Mermet and Gade (2018) found age-related impairments to be dimension-specific and observed a decline, especially for response inhibition, whereas other inhibitory dimensions remained unaffected. This accords well with the particularly relevant role of response inhibition in our studies and the fact that age and prepotent response inhibition in our data revealed a medium correlative association (see Chapter 5).

To summarize, the age-related increase of susceptibility to interference (Bowles & Salthouse, 2003; Fernandes & Grady, 2008) might, in fact, be (partly) mediated by related cognitive functions (Hedden & Yoon, 2006). At least in motor tasks, prepotent response inhibition is likely to mediate such a relationship. In the future, more sophisticated approaches, such as mediator or factor analyses, might help to disentangle the complex interactions between age, cognitive functions and individual interference susceptibility.

Proficiency

In Chapter 2.3.4, we introduced two possible hypotheses on how the degree of mastering a motor skill before it becomes modified might account for successful skill change. Specifically, we raised the question whether the presence of a high skill proficiency is beneficial or detrimental in situations of change. On the one hand, skilled performance appears to be characterized by automatic behavior (Fitts & Posner, 1967) which is likely to produce interference effects. But on the other hand, it is characterized by the ability to flexibly adapt the skill to changed conditions (Ericsson, 2008; Gentile, 1972).

Consistent over all behavioral studies, our data revealed a clear relationship between skill proficiency and amount of interference insofar that those participants with higher typing baseline performance experienced more performance decrements following both types of rule change (see Chapters 4, 5 and 6). Even though the baseline examinations did not include a test of automaticity, it is known and could be well observed that especially fast typists rely on strong proceduralized knowledge and automatisms (Logan, 2018) so that a disruption via rule change led to an enormous slowing of overall typing speed and decrease of accuracy. This observation primarily supports the assumption that a high skill level associated with strong automatisms (Fitts & Posner, 1967) is prone to interference effects and thus rather detrimental in situations of skill change.

At first glance, this data appears to be in contrast to the reported alternative models of motor learning by Ericsson (2008) and Gentile (1972). In fact, both models understand proficient performers as being able to flexibly adapt to changes, which apparently did not seem to be the case in our studies which consistently revealed a disadvantage for performers that started at a high baseline performance. Nonetheless, these alternative models may contribute some relevant aspects to the interpretation of our findings. First, according to Ericsson's model on deliberate practice (Ericsson, 2008), expert performance is characterized by maintained cognitive control and the development of complex mental representation instead of automaticity, which constitutes the highest stage of motor learning in the model by Fitts and Posner (1967). He postulates the achievement of the automatic phase to be useful only for simple everyday skills. As far as complex motor skills are concerned, achieving the automatic phase is assumed to result in arrested development and to be disadvantageous to further improvement. Instead, experts perform ongoing cognitive control and re-evaluation (like in the cognitive and associative phase of the model by Fitts & Posner, 1967), thereby maintaining the ability to improve, change and adapt the existing skill. This was apparently not true for our highly proficient typists who were completely at the mercy of their automatisms and experienced the largest performance decrements. However, Ericsson's model actually tackles exactly the issue that renders the skill change so difficult for fast typists: that is, the strong reliance on automatisms which might be beneficial under regular conditions, but detrimental when it comes to unpredicted changes. In other words, if the typists from our studies would not have been stuck in the automatic phase yet where further development is arrested (Ericsson, 2008), they probably would have managed the rule change more easily. From this point of view, our findings might be in line with Ericsson (2008), since high automatization prevented flexible adaptation and cognitive control.

But is it really worthwhile avoiding all the benefits of automatisms in a regularly well-functioning behavior, just in case a rule change is encountered? On the one hand, one might argue that the specific case of typing indeed reflects an everyday skill (Kalfaoğlu et al., 2018; Yamaguchi, 2019), where reaching the automatic phase might therefore be advantageous. On the other hand, the two-stage model by Gentile (1972) makes a crucial differentiation here: According to this model, the later (second) stage of skill acquisition is characterized by fixation and diversification. Importantly, Gentile (1972) adds a relevant distinction. She argues that whether the acquired skill might be "refined and retained, or [...] markedly altered" (Gentile, 1972, p. 11) is often skill-specific and depends on the nature of environmental control. Whereas task and environmental conditions for closed skills usually remain constant, they are variable for open skills. Therefore, the author asserts that for closed skills which are performed under constant conditions, it is advisable to identify the most effective action strategy and refine this while striving for consistency in execution (which results in fixation). For open skills, in contrast, this strategy might be detrimental. Rather, the performers should establish a broad movement repertoire that enables them to flexibly adapt to different situations. Despite its dependence on continuously changing stimulus content that is almost always novel, typing might represent a more closed skill (note that the classification open versus closed skills are usually understood to represent a continuum; Schmidt & Wrisberg, 2008) which likely became more fixated than diversified in stage two of skill acquisition during the course of learning in our participants (see also Boyle & Ackerman, 2004). Following the two-stage model, high proficiency might make responding to rule changes particularly challenging (Gentile, 1972), which is in line with the observations regarding our highly proficient participants (see Chapters 4 and 5). Hence, the answer to the question whether a high skill proficiency is detrimental or beneficial in skill change situations might depend on whether an open or a closed skill is concerned (Schmidt & Wrisberg, 2008). Assuming typing to reflect a more closed skill, our findings revealing high baseline performance to be detrimental to skill change are well in line with the assumption of previous fixation rather than diversification (Gentile, 1972). This further suggests that a high proficiency does not always need to be detrimental for successful skill change, for instance when the to-be-changed skill reflects an open skill. However, as we only investigated the motor skill of typing within our investigations, future research is required to test this assumption. At the present point, we cannot conclude that a high proficiency, in turn, is generally beneficial for modification of open skills. In fact, performers of open skills – who should have experienced diversification in stage two instead – might nevertheless not be entirely prepared for situations of authentic skill change. Describing the characteristics of this phase, Gentile (1972) states that "the performer must develop a response repertoire in which there are an exact number of motor patterns to match the number of possible regulatory stimulus subsets" (Gentile, 1972, p. 11). Thus, it is conceivable that a rule change, as it was applied in our paradigm or any type of (permanent) skill change, exceeds the scope of this movement repertoire. Therefore, future research should address both open and closed skills.

8.2 METHODOLOGICAL CONSIDERATIONS

Not only does the topic of motor skill change provide little previous research, it also presents considerable methodological challenges. It is particularly difficult to investigate due to two main reasons. First, despite the provision of a definition (see Chapter 2.1), in some situations, it remains difficult to differentiate skill change from the learning of a novel skill. We defined changing automatized movement patterns as “the relatively permanent modification of an already acquired movement pattern while the overall task goals remain the same” (see Chapter 2.1, p. 12). But, in fact, it is not always clear when to speak of a skill modification or a skill acquisition. In theory, especially with advancing course of life, something previously learned - which by some means or other is associated with the new target skill - is actually almost always present. The consideration whether a situation represents a skill change or the acquisition of a novel skill holds critical implications for the interpretation of the nature of potential performance decrements. In fact, the performance level after the manipulation might also incorporate an even higher starting performance of a new skill following positive transfer instead of performance decrements (see also Carson & Collins, 2011). From an experimental point of view, it is therefore important to carefully select a task which, in addition to maintaining the task goal, addresses a behavior that is closely associated with – and ideally visibly affected by a previous one and thus is likely to represent a skill *modification*. This is usually the case when automatisms from the previous skill lead to erroneous tendencies to execute (parts of) an old skill instead of a new one (see Chapters 2.1, 4 and 5).

The second problem involves the critical starting point in skill modification. Previous studies from the motor domain often apply paradigms in which participants acquired a specific motor skill in the lab and subsequently had to modify this recently learned motor behavior (Koedijker, Oudejans, & Beek, 2010; Mühlbauer et al., 2007; Shadmehr et al., 1995). This procedure ensures high control over the learning process and comparable baseline performances. However, beyond not completely representing a skill modification process as it usually occurs in real life, these studies often struggle to find the proactive interference effects that are commonly observed in practice. Instead, these paradigms frequently produce initial facilitation (positive transfer effects) with regard to the modified skill (Pöhlmann, 1994; Schmidt, 2014). In other words, groups that had learned a similar, yet not identical motor behavior before, initially score better than groups which did not practice a similar behavior before at all (cf. Koedijker, Oudejans, & Beek, 2010; Panzer, 2002). When aiming to assess *pre-existing automatized motor* skills, it is usually necessary to address *skilled performance*. Along with the lack of control over the original learning process, this alternative approach has several other drawbacks: Samples are usually quite exclusive (due to the respective skill level required as a pre-requisite) as well as heterogeneous (regarding baseline performance, degree of automatization etc.). Given these methodological difficulties, it is not surprising that this research area consists mainly of case studies so far (e.g., Carson & Collins, 2015; Hanin et al., 2002; Hanin et al., 2004). In fact, the empirical studies in the present thesis constitute some of the first RCT studies that systematically investigate the phenomenon of changing automatized movement patterns (for similiar approaches, see Baxter et al., 2004; Milanese et al., 2016; Milanese et al., 2017).

To this end, a novel experimental paradigm was developed and used for all empirical studies in this work which addresses the motor skill of typing. Most importantly, this paradigm enabled us to investigate motor skill change regarding an *already automatized skill,* while nonetheless applying an RCT design. By tackling a motor skill from everyday life, we were able to address a motor behavior which is already established and usually highly internalized among participants. In fact, the amount of practice of an ordinary person in daily life often equals the amount of practice observed in expert athletes or musicians (Kalfaoğlu et al., 2018), thus representing a kind of *expert skill* (Ericsson et al., 1993). Furthermore, the typing task allowed us to flexibly induce small rule changes which affected only *parts* of the original skill (such as one out of ten fingers, see Chapters 4 and 5; or two out of more than twenty keys, see Chapters 6 and 7), therefore still retaining a high similarity to the original skill. This, combined with the existence of a strong motor automatism constitutes an optimal pre-condition for the emergence of proactive interference (Underwood, 1957; Weigelt et al., 2020). Indeed, all empirical studies revealed this paradigm to be highly successful at interference induction as the data show (see Chapters 4 to 7). Inducing only a small rule change, participants were immediately disrupted in their automatized motor behavior, thereby generating the desired interference effects. Whereas traditional interference paradigms generate interference mainly arising from stimulus-specific declarative material such as word lists (cf. Friedman & Miyake, 2004; Kane & Engle, 2000), we were able to create a novel paradigm addressing interference emerging from a pre-existing and procedural skills.

Another key advantage of the applied typing paradigm is related to the ability to measure task performance (Yamaguchi, 2019). By being able to assess reaction time and errors for every single keystroke, not only the final performance outcome but also single components of the movements can be quantified in detail, providing almost a temporally continuous measure of performance. As a result, various performance parameters (such as total time, total errors, IKSI and errors on specific keys) were available to describe and characterize the motor behavior in detail (see Chapters 4 to 7).

Especially working with skilled touch-typists enabled us to assess typing behavior precisely. Following the touch-typing system, every key on the keyboard and thus letter in the stimulus material is mapped to a concrete finger (Scaltritti et al., 2018). Hence, examining typing performance of these participants enabled us to identify not only every key pressed in a sequence but also the concrete finger that pressed the specific key. In fact, the typing paradigm represents a kind of button-press task (with all its advantages with regard to experimental control and quantifiability) which at the same time still encompasses a highly ecologically valid complex motor behavior (Kalfaoğlu et al., 2018).

However, a central limitation of using everyday skills as experimental behavior is that even though it is highly appealing to additionally investigate long-term effects of an intervention, researchers must be aware of their ethical responsibility as, in case of long-lasting changes, these should be beneficial to the participants' skill and not cause a permanent deterioration. Since our study was not designed to improve a skill but, on the contrary, to intentionally induce interference which was supposed to lead to a performance deterioration, the focus of the experimental investigation was mainly on short-term effects (cf. Snyder & Logan, 2013). Note that we defined changing automatized movement patterns as "a relatively permanent modification" (see Chapter 2.1, p. 12). Indeed, it would be interesting for future research to look at how interference diminishes over time and observe the time course over several experimental sessions (e.g., Baxter et al., 2004; Carson & Collins, 2016). However, when conducting long-term studies, a set of participants must be found who are a) currently facing a need for change and/or b) willing to undergo such a change process (for instance, when working with athletes, e.g., Carson & Collins, 2015; Hanin et al., 2002). The latter issue is especially critical regarding little a-priori knowledge about the effectiveness of interventions to date in the area of motor skill change.

Following the requirements posed by the critical rule change, for some of the present empirical studies the samples turned out to be quite exclusive, that is when skilled touch-typists were required as participants (see Chapters 4 and 5). Unfortunately, even if typing in general is a very common skill in Germany, only few people acquired the official touch-typing system during education. Since modern technologies nowadays easily excuse typing errors (which was different back in times of typewriting), many individuals make up their own typing strategies ranging from hunt-and-peck strategy to a more or less systematic use of more than two fingers (Feit et al., 2016). Nonetheless, an exclusive set of highly skilled participants, some of which even practice competitive touch-typing, was assessed. This led to generally small sample sizes (n = 22 in Chapter 4; n = 30 in two groups in Chapter 5). This availability problem was tackled by applying a different manipulation in the subsequent studies (Chapter 6 and 7), that is the realization of a rule change via a key switch (Gordon et al., 1994; Jordan, 1995; Yamaguchi & Logan, 2014), which eliminated the need for the presence of a specific finger-key mapping. Even though this manipulation constitutes another type of constraint (refer also to Chapter 2.1, Chapter 6 and Newell, 1986), both rule change manipulations turned out to be able to successfully induce the intended proactive interference effects (see Chapters 4 to 7) and could therefore be used for future empirical investigations.

A series of task and individual factors were found to be associated with the amount of interference experienced. Importantly, in line with traditional interference paradigms (Schmidt, 2014), also the present paradigm enabled us to look only at a by-product of interference (performance decrements). Hence, strictly speaking, we cannot conceptually distinguish whether following a certain manipulation or disposition less interference is present or whether interference is simply overcome more easily and faster. Following a comprehensive understanding of the factors accounting for the amount of interference, future designs might tackle this question once they are able to determine the expected task-related amount of interference a-priori (by quantifying similarity and other to-be-identified relevant task factors). Detecting deviations from this expected amount, it might be possible to deconstruct the observed amount of interference and to differentiate the amount that arose due to task properties from that driven by individual factors. While bearing a lot of potential, the development of such approaches certainly requires a deeper understanding of the factors which influence the extent of interference.

As far as the assessment of executive functions is concerned, an immense number of tests exists in order to determine one's cognitive abilities (R. C. K. Chan et al., 2008). The different tests used in the reported studies were selected based on relevant literature (Diamond, 2013; Eriksen & Eriksen, 1974; Friedman & Miyake, 2004; Kane & Engle, 2000; Monsell, 2003) as well as on availability of the test material. As elaborated earlier (see Chapters 2.3 and 6), regarding test selection we opted for treating inhibition as a multidimensional construct (Friedman & Miyake, 2004) and therefore administered two (Chapter 5) and three (Chapter 6) different tests of inhibition instead of only one. This decision turned out to be highly meaningful as is stressed by the results (see Chapters 5 and 6) and also underlines the need for future studies in any field of research to treat inhibition as multidimensional. However, also the classification of inhibition as well as the test selection regarding different inhibition subdimensions offer various alternatives and should be considered carefully with regard to the intention of the respective study (Brydges et al., 2012; Friedman & Miyake, 2004; Xie et al., 2017). For instance, it would be interesting to administer not only stop-signal paradigms but also stop-change paradigms in the future, since these paradigms do not only involve the inhibitory component, but also the implementation of an alternative action, as is the case in real life motor skill situations (for a review, see Boecker et al., 2013). Additionally, as mentioned in Chapter 5, the different executive function tests seem to pose quite different task demands. Traditional proactive interference tests mainly focus on proactive interference arising from declarative memory contents (e.g., Kane & Engle, 2000; May et al., 1999; Tolan & Tehan, 1999). As discussed earlier in this thesis, specific proactive interference tests might be needed in the future to predict proactive interference arising from procedural, stimulus-unspecific memory contents (see Chapters 6 and 8.1).

Moreover, combining the typing paradigm with electrophysiological assessment constituted a particularly sophisticated approach by taking a truly complex motor behavior into the EEG cabin. As any kind of head movements generally produce strong movements artifacts, assessing the electrophysiological correlates of motor behavior using EEG is very challenging (Doppelmayr & Amesberger, 2012). Not for nothing, motor responses in many psychological EEG experiments are limited to single button presses and EEG studies in the field of sport often focus on aspects like movement preparation, motor imagery or attention with little range of movement (Doppelmayr & Amesberger, 2012; Hatfield & Kerick, 2012). However, despite constituting a complex motor behavior, typing is still relatively suitable as motor task during

EEG recording. Nonetheless, a series of perils remain and as a result little research has been done on the electrophysiological correlates of typing so far (for exceptions, see de Jong et al., 1995; Kalfaoğlu et al., 2018; Logan et al., 2011; Pinet et al., 2015; Pinet et al., 2016; Scaltritti et al., 2018; Scaltritti et al., 2020). While addressing different aspects of motor planning and linguistic processing, none of these studies was dedicated to motor skill change and interference control.

As mentioned in Chapter 7, one of the remaining major challenges when combining typing tasks and EEG recording is posed by eye movements which often cause strong movement artifacts and immensely decrease the signal-to-noise ratio of the measurement (Luck, 2014; Zschocke & Hansen, 2012). To deal with this problem, scientists often only recruit participants who are able to blind type (Pinet et al., 2016; Pinet et al., 2019; Scaltritti et al., 2018), administer elaborated artifact correction and rejection procedures (Kalfaoğlu et al., 2018) or assess only electrophysiological response prior to or around the first keystroke (Pinet et al., 2015; Pinet et al., 2016; Scaltritti et al., 2018). Besides the fact that even skilled touch-typists happen to get their fingers out of place on the keyboard, leading to a series of consecutive errors without noticing, eliminating visual control during typing would not have been suitable for our paradigm. In fact, the fundamental aim of our rule change manipulations is to induce proactive interference and a change in the visual strategies appears to be a direct consequence of this rule change (see also Chapters 5 and 8.1.1). To this end, an innovative set-up was developed for the present typing paradigm, reducing the need for eye movements while still allowing the participants to monitor their hands and keyboard as well as the screen. Specifically, a small external monitor was placed directly above the keyboard presenting the stimulus words (Figure 7-1), while the head of the participant was fixated facing downward with an inclinable chinrest. Consequently, both keyboard and screen were present in the same visual field, eliminating any need for head movements and reducing eye movements to a minimum. In contrast to previous studies, we were able to explicitly allow for visual attention towards hands and keyboard, therefore assessing a more natural typing behavior. The effectiveness of this set-up, which to our knowledge has never been reported so far, was observable in the quality of the EEG data.

Finally, previous EEG-based typing studies mainly focused on ERPs (or LRPs respectively) locked onto the stimulus onset or first keystroke only (Logan et al., 2011; Pinet et al., 2015; Scaltritti et al., 2017; Scaltritti et al., 2018). Other studies specifically investigating response inhibition (applying e.g. stop paradigms) typically compute only stimulus-locked ERPs (Dimoska et al., 2006; Kok et al., 2004; Wessel & Aron, 2015; for exceptions see Ramautar et al., 2004, 2006). In the present study, we used the same method, but extended the conventional data analysis by analysis of response-locked ERPs, even locked to keystrokes beyond the first finger movement (see Chapter 7), thus providing further insights into the electrophysiological correlates of motor behavior.

There is much room for future research to further unravel the electrophysiological correlates of both typing as a complex motor skill (Kalfaoğlu et al., 2018; Scaltritti et al., 2017; Yamaguchi, 2019) and motor skill change in general. Here, electrophysiological assessment bears the advantage of providing an online measure of the (time course of) neuro-cognitive processes at play in the specific moment of interference control. In the future, the methodology could be extended by other online measures such as kinematic motion tracking (Feit et al., 2016) which offers an option to quantify performance with regard to other parameters such as performance variability or movement efficiency. From a neuroscientific perspective, studies using fMRI – which offers a higher spatial resolution – might provide future insights into the brain structures that are involved in proactive interference control and other processes associated with motor skill change (cf. Cothros et al., 2006; Graybiel, 2008; Simmonds et al., 2008).

8.3 FUTURE DIRECTIONS & OUTLOOK

To conclude, the current work revealed that motor skill change may be accompanied by proactive interference and that the amount of interference one experiences when performing a skill change is highly variable and depends on several task-related and individual factors. These findings provide several open doors for future research.

First and foremost, it has been shown that proactive interference does not only arise from purely declarative contents, as is widely known from traditional interference tests (see Friedman & Miyake, 2004; Kane & Engle, 2000; Rosen & Engle, 1998; Tolan & Tehan, 1999), but also from procedural, stimulus-unspecific sources, such as automatized behavior. Whereas research in the past has mainly focused on interference from declarative memory, there is a broad scope for future research to develop tests and experimental paradigms that assess proactive interference from *procedural* skills (Koedijker, Oudejans, & Beek, 2010; Mühlbauer & Krug, 2007; Panzer, 2002). In this context, interference may not only arise from skills that are learned during an experiment, but also from pre-existing skills that have been proceduralized prior to the experiment (cf. habits in Graybiel, 2008) as was the case in the present approach (see also Chapter 8.2).

Regarding the task-related factors, we assessed the usefulness of a motor restriction which eliminated a strong, but unwanted action tendency and was intended to function as a type of inhibition support. To recapitulate, interference was proposed to emerge following the competition of two (or more) action alternatives. While the primary approach for interference control in the current work aimed to suppress the irrelevant option, the opposite strategy, i.e. increasing the salience of the relevant option, might also be a successful tool for overcoming interference (for a related discussion, see Levy & Anderson, 2002). Future research might look at various options for implementing such a salience enhancement, which might be realized via, e.g., the direction of visual attention (Hagemann et al., 2006) or motor guidance (Kümmel et al., 2014).

While, in the current thesis, action constraints (Chapter 2.2) and interindividual differences (Chapter 2.3) were mainly studied separately, a future step could be to combine both approaches by, e.g., scrutinizing whether a motor restriction might be more or less beneficial as a function of individual characteristics. For example, tying in with our findings, it is conceivable that the motor restriction strategy – which is intended to function as a kind of inhibition support – might be particularly beneficial for individuals with poorer prepotent response inhibition abilities or where temporarily less cognitive resources are available (see also Chapter 4 and 8.1). Hence, it is appealing for future research to also take a closer look at the interaction between task-related and individual factors and their potential effects on skill change procedures. In addition, also regarding the motor restriction, electrophysiological investigations might be insightful by assessing how wearing a motor restriction might influence amplitude and latencies of event-related potentials associated with interference control (cf. Facchini et al., 2002; Liepelt et al., 2009).

Of course, besides the motor restriction, several other task-related factors may potentially affect the amount of interference which on the one hand might become a topic for future studies but on the other hand may also be of relevance when developing study designs. Such factors could include similarity of actions (e.g., Kostrubiec & Zanone, 2002; Pöhlmann, 1994; Underwood, 1957; Weigelt et al., 2020), necessity and reasons for change (Chapter 2.1), change intention (shift or bifurcation; Carson & Collins, 2011), task modality (e.g., Ascoli & Schmidt, 1969; Lustig et al., 2001) or temporal distance (e.g., Mühlbauer & Krug, 2007; Shadmehr et al., 1995; Shadmehr & Brashers-Krug, 1997).

In addition to task-related factors, several individual factors turned out to be associated with the amount of interference following a motor skill change (i.e., proficiency, age and inhibition). Even though they are often associated (especially in our paradigm), proficiency and automaticity do not always seem to have a linear relationship (cf. Ericsson, 2008; Gentile, 1972). Therefore, separate tests of automaticity regarding the skill of interest would definitely be useful in the future when examining interindividual differences in the amount of interference (cf. Logan, 1985; Schmidt, 2014). Moreover, the identification of the reported individual variables might not only be profitable for the theoretical understanding, but also for practice. First, since they predict the amount of performance deterioration in motor skill change process, assessing individual parameters could serve as a diagnostic tool for costs of change processes (Oreg, 2003). Importantly, besides the factors investigated in the present work, psycho-social variables such as commitment, trust and confidence have also been reported to mediate the success of skill change processes (Carson & Collins, 2016) which might need to be taken into account. Second, cognitive skills seem to be trainable (for a review, see Diamond, 2013) – which also encompasses a constraint variation (Huster et al., 2013). Consequently, this has promising implications for potential interventions facilitating motor skill change by enhancing, e.g., inhibitory skills such as via cognitive and motor training (e.g., Diamond & Lee, 2011; Gottwald et al., 2016; Leshem et al., 2020; Zhao et al., 2018) or even modern brain stimulation techniques (e.g., Ditye et al., 2012).

Finally, the present research mainly pursued a basic science approach aiming to understand the cognitive mechanisms underlying motor skill change processes. Certainly, one of the goals in the long run should be the transfer of theoretical findings into practice. Therefore, in the future, it is necessary to also address other motor skills to broaden the scope and investigate both open and closed skills (see Chapter 8.1.3; Gentile, 1972; Schmidt & Wrisberg, 2008). This distinction might indeed not only be relevant for the impact of skill proficiency (see Chapter 8.1.2) but possibly also for other factors. Once the mechanisms are better understood, more ecologically valid studies might be conducted, as more authentic real-life problems can be tackled which also involve a given necessity to change an existing skill. Then, also elite performers might be willing to participate in studies which affect their current motor behavior in the long run. While important initial research has conducted single-case studies (e.g., Carson & Collins, 2015; Hanin et al., 2002; Hanin et al., 2004), further theory-driven RCT studies need to be conducted. Performers and coaches might then receive evidence-based advice for the practical applications in order to reduce the costs in motor skill change and successfully guide and optimize motor skill change processes (cf. Chapter 2.1). The research presented in this thesis suggests that we are indeed able to optimize skill change processes, but also that more systematic research is required to further corroborate the findings and transfer them into practical applications.

To refer back to the introductory quotation by Heraclitus, changes are inevitable in life and it will always remain necessary to respond to these changes. By addressing the issue of performance deterioration and uncovering a series of influencing factors including age, inhibition, proficiency and action constraints, this thesis aimed to provide a first step in expanding the scientific understanding of motor skill change and thereby opened pathways for future research on this topic.

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Ich bestätige, dass mir die geltende Promotionsordnung der Fakultät für Sozial- und Verhaltenswissenschaften der Friedrich-Schiller-Universität bekannt ist. Ich habe die vorliegende Dissertation selbst angefertigt, keine Textabschnitte eines Dritten oder eigener Prüfungsarbeiten ohne Kennzeichnung übernommen und alle von mir benutzten Hilfsmittel, persönlichen Mitteilungen und Quellen in meiner Arbeit angegeben. Die in dieser Arbeit inkludierten bereits veröffentlichten oder eingereichten Publikationen sind in Zusammenarbeit mit den genannten Ko-Autoren entstanden, welche an der Studienplanung, -auswertung und Erstellung der entsprechenden Manuskripte mitwirkten. Ich bestätige weiterhin, dass die Hilfe eines kommerziellen Promotionsvermittlers nicht in Anspruch genommen wurde und dass Dritte weder unmittelbar noch mittelbar geldwerte Leistungen von mir für Arbeiten erhalten haben, die im Zusammenhang mit dem Inhalt der vorgelegten Dissertation stehen. Diese Dissertation wurde nicht zuvor als Prüfungsarbeit für eine staatliche oder andere wissenschaftliche Prüfung eingereicht. Ebenfalls habe ich zuvor nicht die gleiche, eine in wesentlichen Teilen ähnliche oder eine andere Abhandlung bei einer anderen Hochschule als Dissertation eingereicht.

Jena, 28.01.2021
Ort, Datum

Laura Sperl
Unterschrift