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The Effects of Attentional Directions and Multisensory Action Effects on Motor Skill Performance

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1 Introduction

Motor skills are an essential component in our daily life. Humans show a remarkable capacity of motor skill acquisition, ranging from tying a necktie to dribbling a soccer. According to the model proposed by Fitts and Posner (1967), learners acquiring a new motor skill typically go through a series of relatively distinct stages from a controlled, attention-demanding stage to an automatic stage. In the first stage, the cognitive stage, large parts of the motor skill are controlled consciously, and motor skill execution is slow, non-fluent, and error-prone that is the hallmark of a novice. With practice, learners next enter the associative stage, which consists of a mixture of conscious and automatized control strategies. After extensive practice, learners gradually reach the autonomous stage, in which cognitive control is reduced to a minimum, and motor skill execution is efficient, consistent, and highly precise.

How can motor skill acquisition be facilitated, and how can motor skill performance be optimized for performers at different stages are central questions for researchers who are concerned with motor skill from a theoretical perspective. Over the past 20 years, researchers in motor skill learning and performance have generated several lines of evidence that indicate important roles of attentional direction and action effects in motor skill performance and acquisition. The present dissertation examines how the effects of different attentional direction change within individual with practice and investigates the role of action effects from multiple sensory modalities perspective. Firstly, the dissertation briefly describes previous findings and theoretical background regarding the influence of attentional direction and action effects and. Secondly, weaknesses in prior research and remained questions are identified, which lead to the specific topics that were examined in three empirical studies. Two articles that have been published in international peer-reviewed journals and one submitted article are subsequently described, which is followed by a discussion and conclusion in the end.

1.1 Attentional direction and dual task

Research has consistently found differences in the attentional demands required for motor skill execution inter-individually between novices and experts or intra-individually between newly acquired and well-learned motor skills (e.g., Beilock et al., 2002; 2004; Leavitt, 1979). According classic theories of motor skill acquisition and automaticity, low-skilled performers need to keep declarative knowledge about motor skill execution in working memory and attend to the components of motor skill execution in a step-by-step fashion (Anderson, 1982; Fitts & Posner, 1967). On the other hand, highly skilled performers use procedural knowledge, which does not require the same level of attention, to drive motor skill execution, which thus becomes automatic (Anderson, 1982; Fitts & Posner, 1967).

The differences in attentional demands of motor skill execution have led to research investigating how the attentional direction—either by directing attention toward execution or by shifting attention away from execution—affect performance across levels of expertise. To investigate how the direction of attention influences the motor skill performance across skill levels, previous studies have employed a "dual-task methodology." This term refers to experiments in which participants are required to perform both a primary task related to the motor skill and a concurrent task, generally cognitive in nature. The concurrent cognitive task is used to either direct participants' attention to any aspect of the motor skill execution or shift participants' attention away from execution (Beilock et al., 2002; Castaneda & Gray, 2007; Gray, 2004).

1.1.1 Skill-focused dual task and extraneous dual task

Two categories of concurrent cognitive tasks have been distinguished depending on the attentional direction they induce: skill-focused dual task and extraneous dual task. The skill-focused dual task refers to a concurrent cognitive task that induces a skill-focused, internal focus of attention toward execution. In this type of task, participants are asked to explicitly report a particular part of the motor skill execution according to a stimulus. For example, in a soccer dribbling task, participants were asked to identify which side of their foot was touching the ball when they heard a tone sound; in a baseball-batting task, participants had to identify the direction of the bat when a tone was played (Beilock et al., 2002; Gray, 2004).

The extraneous dual task refers to a concurrent cognitive task that induces attention to anything in the environment not directly involved in the motor skill execution and shift attention away from execution. This type of cognitive tasks can include identifying geometric shapes (Leavitt 1979), counting backwards (Nicolson &

Fawcett, 1990), detecting auditory probes (Abernethy, 1988), and tone counting (Nissen & Bullemer, 1987).

1.1.2 Effect of attentional direction on the Performance

Previous studies have found that attentional direction effects, as manipulated by dual tasks, on motor skill performance are expertise dependent. Novices have shown some benefits from a skill-focused dual task in comparison with an extraneous dual task (Beilock et al., 2002; 2004; Gray, 2004). It has been argued that to novices' performance a skill-focused dual task is not disruptive because the novices are executing the task consciously in a step-by-step manner and the motor skill execution of novices is attention-demanding and governed by declarative knowledge structures (Anderson, 1983; Fitts & Posner, 1967; Ford et al., 2005). Thus, the skill-focused dual task directs their attention to what they are expected to be attending (Diekfuss et al., 2017). In contrast, novice's performance is impaired in an extraneous dual-task condition because during motor skill execution novices have to attend to extraneous sensory information which occupies resources needed for motor skill execution (Beilock et al., 2002; Gray, 2004; Nissen & Bullemer, 1987).

However, experts generally show superior performance in an extraneous dual-task condition than in a skill-focused dual-task condition. It has been argued that the extraneous stimulus of the concurrent cognitive task does not greatly impair performance of experts, because their motor skill execution has become proceduralized in long-term memory and requires little attention (Anderson, 1983;

Castaneda & Gray, 2007; Gray, 2004). Consequently, they can direct most of their attention to processing the extraneous dual task without the impairment of the primary task performance (Beilock et al., 2002). In contrast, experts' performance is impaired when a skill-focused dual task is introduced, because this type of concurrent cognitive task forces them to monitor the process of execution and refocus their attention on the specific components of the motor skill, which leads to the breaking down of automatic mechanisms (Beilock & Carr, 2001; Ford et al., 2005). Experts in this situation are believed to reinvest in the step-by-step controlling process, and use declarative knowledge, which is brought back into working memory, to complete the motor skill execution (Masters et al., 1993).

In a study by Gray (2004), novices and experts were asked to complete a motor task of simulated baseball batting under dual-task conditions. During each trial, one of two different tones (either 250 or 500 Hz) occurred during the swing phase of baseball batting. In the skill-focused dual-task condition, participants were required to monitor the direction of their swing and verbally indicate whether the tone occurred during the downward or the upward phase of the swing at the instant the tone was presented; in the extraneous dual task condition, participants were required to monitor the frequency of the tone and indicate whether the tone was the higher or the lower pitched tone at the instant the tone was presented. Novices' batting performance was better in the skill-focused dual-task condition than in the extraneous dual-task condition, but experts displayed superior batting performance in the extraneous dual-task condition relative to the skill-focused dual-task condition. Similar results have been reported for a soccer dribbling task (Beilock et al., 2002; Jackson et al., 2006) and a golf putting task (Beilock et al., 2002; Beilock & Gray, 2012).

1.2 Action effect and ideomotor theory

Human actions are generated to bring about desired and expected action effects in the environment (e.g., write a manuscript to publish our research; reach for a bottle of beer to drink it, press “l” on the keyboard to make the letter appear on the screen). The idea that these action effects drive our actions—even motor actions—is the central tenet of the ideomotor theory (Shin et al., 2010; Stock & Stock, 2004). According to the ideomotor theory, action effects are important parts of an action’s mental representation (Greenwald, 1970; Hommel et al., 2001; Kunde et al., 2004). Learning or performing a particular action requires the acquisition of associations between actions and their effects (Elsner & Hommel, 2001). After the associations have been acquired, action effects can subsequently be used to prime and facilitate performance of that action (Elsner & Hommel, 2001; Greenwald, 1970; Hommel, 1996). Thus, an action is bidirectionally associated with its action effects (Greenwald, 1970). Previous research has shown that anticipation of action effects is an essential component underlying actions (Kunde et al., 2007), can prime the action (Elsner & Hommel, 2001; Kunde, 2001; Kunde et al., 2004), and also plays a crucial role in the acquisition and execution of motor sequences (Hoffmann et al., 2001; Stöcker & Hoffmann, 2004; Stöcker et al., 2003).

1.2.1 The influence of action effects on simple action

In a study by Elsner and Hommel (2001), during an acquisition phase, participants were free to press either the left or right key in response to a centrally presented visual signal. Each key, however, contingently triggered either a high or low tone. In the test phase, participants were asked to respond to these tone signals by pressing one of the same two keys. Participants responded faster to a tone if they had to press the key that had previously triggered that tone, compared to the other key. Further, when asked to freely choose which key to press in response to a tone, participants preferred to press the key that had previously triggered that tone.

More straightforwardly related to the assumption that anticipation of action effects generates action, studies have also investigated whether predictable action effects still have an impact on an action despite following the action, and thus being retroactive. Studies on the response-effect compatibility have repeatedly shown this to be the case. For example, in a four-choice reaction time paradigm, participants responded faster when the responses’ location spatially corresponded to the location of the responses’ visual effects (one of four horizontally aligned boxes lit up on a monitor; task-irrelevant) than when locations did not spatially correspond. Additionally, in a two-choice task, participants initiated a certain force faster when the action triggered auditory effects of corresponding, rather than noncorresponding, intensity (Kunde, 2001). The response-effect compatibility effect has been reported for many task variations and relations between responses and effects (Koch & Kunde, 2002; Kunde, 2001, 2003; Kunde et al., 2004). Thus, although sensory effects are technically irrelevant when the actor only has to respond to a trigger stimulus and the effects follow this response, the effects or their anticipation still serve a function in selecting the response (Hommel, 2009). Moreover, anticipated action effects also influence the initiation of the response – if a temporal delay is introduced in experiments between the response-triggering stimulus and an actual go-signal response-effect compatibility effects can still be found (Kunde et al., 2004). In the response-effect compatibility paradigm, it has also been found that anticipated effects can influence response execution, indicated by contrast effects. If the task is meant to produce a forceful response, effect intensity has been shown to uniquely affect the peak force of soft and forceful responses, whereas quiet tones increase the peak force of both soft and forceful responses, relative to loud tones, and vice-versa (Kunde et al., 2004). Taken together, there is strong evidence for the assumption that action effects following actions are fundamental to action generation and execution.

1.2.2 The influence of action effects on motor sequence

Given that a significant amount of everyday behavior is structured in sequential succession, and our actions sequentially interact with effects in the environment, the role of anticipation of action effects has also been studied in relation to learning of motor sequences. Motor sequences are considered the building blocks of more hierarchically controlled and complex motor skills (Rhodes et al., 2004).

Learning of motor sequences is often investigated within a serial reaction task (SRT) paradigm, wherein participants are asked to respond to successively presented stimuli, and each response triggers the next stimulus presentation. In a classic study by Nissen and Bullemer (1987), when stimuli were repeatedly presented in a fixed order, reaction time decreased more with practice, compared to stimuli presented in random order. Since each response triggered the next stimulus, Ziessler (1998) posited that participants might treat the presentation of the next stimulus as an action effect of the present response. With practice, an association forms between response and effect (the presentation of the next stimulus). The anticipation of the next stimulus can prime the current response, which contributes to serial learning. Subsequently, Ziessler and Nattkemper (2001) showed that serial learning in SRT is based on learning the relations between responses and subsequent stimuli. The effect of each response in the traditional SRT paradigm is task-relevant since it serves as the stimulus for the next response as well. Furthermore, task-irrelevant action effects from auditory modality, such as tone effects, also influence the serial learning in SRT (Hoffmann et al., 2001). The reaction time to ordered stimuli was faster for the experimental group with tone effects than for the control group without tone effects, if tone effects irrelevant to the task were contingently mapped to the responses. Based on such findings, it has been argued that stable associations not only develop between responses and their effects but also between the successive effects themselves (Greenwald, 1970). Greenwald (1970) postulated that for sequence control, eventually the representation of the sequence of (anticipated) effects takes over response control. After repeatedly experiencing stimulus-response-effect triplets, sensory effect production leads to the anticipation of the next effect, which in turn triggers the next response. This process can be viewed as effect chaining; however, its consequences are less visible in the classic SRT task, as each response (also) occurs in response to a stimulus.

If an entire sequence needs to be learned and reproduced—for example, a piano melody—effect chaining should be more evident. In a study by Stöcker and Hoffmann (2004), participants learned two motor sequences: a short sequence of three ordered letters and a long sequence of six ordered letters. In one group of participants ("tone-group"), each keypress was followed by an immediate tone effect that was distinctively and contingently mapped to the keypress. The tones were of the C-major scale and mapped to the keys from left to right, in ascending order. The other group of participants received no auditory effects ("no-tone group"). The two sequences were learned within an SRT paradigm, with each letter of a sequence first presented as a stimulus on a computer monitor, to which participants then responded, resulting in a contingent effect (or none), and after a short interval, the next letter of the sequence was presented. Additionally, a sequence label on the screen always indicated which of the two sequences was presented. Performance was assessed within a choice reaction time paradigm. After the label indicating which sequence was to be executed (the short or the long sequence) appeared on the screen, participants were to correctly reproduce the whole sequence as quickly as possible. It was assumed that, compared to the no-tone group, effect chaining in the tone group would not only lead to faster reaction times but also to "chunking" the elements of the sequence into a larger unit. Based on the general finding that motor sequences with fewer elements are initiated faster than motor sequences with more elements (Verwey, 1999), the initiation times

(ITs) of motor sequences would presumably be smaller in the tone than in the no-tone group. Results showed both motor sequences were initiated significantly faster in the tone group. This effect is associated with shorter interresponse times (IRTs; i.e., the transition between keys within a sequence) in the tone group than no tone group. These findings supported that auditory action effect chaining in the tone group lead to faster initiation and execution of motor sequences.

1.3 Weakness and gap in literature

The described studies provided insights into the roles of attentional direction and action effects in motor skill performance and acquisition, however, some weaknesses and research gaps in prior research can be identified. I will describe them on the topics of attentional direction and action effects separately.

1.3.1 Weakness and gap in literature related to attentional direction

Despite empirical findings that the effects of attentional direction, as manipulated by dual tasks, on the performance of motor skills differ as a function of skill level, some weaknesses and gaps in prior research can be identified.

First, existing inferences are based mostly on inter-individual comparisons between individuals at different skill levels of the motor skill involved. The differences between individuals at different skill levels may thus reflect (at least in part) previously existing inter-subject differences, such as differences in general performance, preferences for different attentional foci, or different working memory capacities. The differences may thus not particularly reflect changes in motor processes with practice, which would need to be investigated via a longitudinal, intra-individual approach.

Second, studies thus far have looked mostly at effects on performance outcomes (such as the time required to complete a slalom course), and to some extent at effects on movement execution (Beilock et al., 2002; Jackson et al., 2006), but not at effects on information processing. If a simple information-processing stage model of motor skill is assumed, at least a selection stage, an initiation stage and an execution stage can be distinguished (Dudman & Krakauer, 2016; Kunde et al., 2004). To execute a motor task, a person is first required to select and initiate the proper movement sequence which is then executed. The efficacy of information processing involved at these stages could influence the performance of the motor skill, and the effect of attention directions might differ not only as a function of the amount of practice but also depending on the stage of information processing.

1.3.1 Weakness and gap in literature related to action effects

Previous studies on the influence of sensory action effects on motor sequence performance focused on the influence of a unimodal action effect. However, the role of action effects from multiple sensory modalities perspective has not been investigated.

Stöcker and Hoffmann (2004) showed a beneficial influence of the task-irrelevant action effects from one modality (auditory), compared to no auditory effects. The action effects in the original Stöcker and Hoffmann paradigm consisted of kinesthetic feedback from the fingers and proprioceptive perception of responses (Greenwald, 1970). When they are augmented by contingent sensory effects from an auditory modality (i.e., tones), all these sensory effects form the coherent action effects. The action effects from different modalities are coded into the action representation as different features of an event file in a distributed fashion (Hommel, 2004). These multimodal features are becoming effective retrieval cues or primes of the associated movement pattern. Numerous studies (e.g., Ladwig et al., 2013; Sedda et al., 2011; Zmigrod et al., 2009) have provided evidence for interactions between features from different sensory modalities and between multisensory features and actions. Action effects from different modalities interact with each other, making the associations between action and effect and between successive actions appear to grow stronger (Kunde et al., 2004; Stöcker & Hoffmann, 2004). It may be speculated that the more action effect features are present and anticipated, the greater the activation of the representation of actions and the stronger the associations between successive actions. If this were the case, task-irrelevant action effects from multiple sensory modalities could prime the action more efficiently and make the associations between successive actions stronger than task-irrelevant action effects from a single sensory modality.

2 The dissertation research

Three research articles have been written. In the first article, I investigated the performance of motor sequences under two different dual-task conditions (skill-focused and extraneous) across practice, applying a longitudinal, intra-individual approach. Moreover, by assessing different components of skill performance, I also addressed whether the preparation phase and the execution phase of motor skill are affected differently.

In the second article, based on the results of the research reported in the first article, I conducted a follow-up study to understand in-depth the effects of the dual tasks on the preparation phase of motor skill across practice. I disentangled the effects of the dual tasks on the selection and initiation stages of motor sequence across practice. The experimental design in this study was nearly identical to the paradigm in the first article, with one exception. I used different stimulus onset asynchronies (SOA) between sequence label cue and a starting signal to dissect the preparation phase into sequence selection and sequence initiation stages.

In the third article, I investigated the role of task-irrelevant action effects from a multisensory perspective and test whether there was an advantage for bimodal action effects on motor sequence performance, compared to unimodal action effects. Specifically, we compared the initiation and execution of motor sequences of participants who received different action effects in an auditory, visual, or audiovisual condition.

3 Methods

3.1 Article 1

I adapted a motor sequence task paradigm (Stöcker & Hoffmann, 2004) and a dual-task paradigm (Gray, 2004). Participants were instructed to learn and then explicitly practice two fixed motor sequences (a three-key and a six-key sequence). During the practice of the two sequences, a tone, either low- or high-pitched, was presented randomly at one of the keypresses during each execution of the motor sequence. As a concurrent cognitive task, participants had to indicate, after executing the motor sequence, either the pitch of the tone (in the extraneous dual-task condition) or the key at which the tone was presented (in the skill-focused dual-task condition). I monitored the participants' performance of motor sequences to find out how the effects of dual tasks change with practice. I used reaction time (RT, also known as initiation time or first-response time) and movement duration (MD, also known as movement time) as indicators of the performance of the motor sequences. RT refers to the time needed to select and initiate a motor sequence execution; MD refers to the amount of time needed to actually execute a motor sequence. Further details on the participants, measures and procedure are stated in the original article.

3.2 Article 2

The experimental design in this study was nearly identical to the experimental paradigm in Article 1, with one exception. I used different stimulus onset asynchronies (SOA; 0, 300, 900 ms) between sequence label cue and a starting signal to give varying amounts of preparation time. I used RT as an indicator of the performance of the preparation phase of motor sequence. I compared the difference in RT between dual-task conditions in different SOA conditions. The rationale for manipulation of SOA conditions was that if varying SOAs have no differential influence on RT difference between dual-task conditions, it would indicate that attentional direction does not affect sequence selection. If attentional direction's effect decreases with increased SOAs, it would indicate that attentional direction's influence appears in sequence selection and/or sequence initiation stages. And if attentional direction's effect is ruled out by sufficiently long SOAs, it would indicate that attentional direction's influence appears only during the sequence selection stage. Moreover, I also used movement duration (MD) as indicators of the performance of the execution of motor sequence. I wanted to explore whether the performance of the execution stage was affected by different SOA conditions. Further details on the participants, measures and procedure are stated in the original article.

3.3 Article 3

I adapted a motor sequence task paradigm (Stöcker & Hoffmann, 2004) and compared motor sequence performance of participants who received different action effects in an Auditory, Visual, or Audiovisual condition. Each participant practiced two motor sequences (a three-key and a six-key sequence). The mapping of task-irrelevant action effects to keypresses differed in each group. In the Auditory condition, keypresses produced tones of a C-major scale mapped to keys from left to right in ascending order. In the Visual condition, keypresses produced rectangles in different locations on the monitor mapped to keys from left to right in ascending order. In the Audiovisual condition, both tone and rectangle effects were produced simultaneously by keypresses. Initiation times (ITs) and mean interresponse times (mean IRTs) were measured as indicators for motor sequence performance. Further details on the participants, measures and procedure are stated in the original article.

4 Publications

4.1 Article 1

Authors: Mengkai Luan, Arash Mirifar, Jürgen Beckmann & Felix Ehrlenspiel

Title: The Varying Effects of Dual Tasks on the Performance of Motor Skills across Practice

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Summary:

The present article examined how the effects of different attentional conditions change within individuals with practice, by using a dual-task methodology within an intra-individual design. Participants were instructed to learn two motor sequences (three versus six keys) and then practiced under two block-wise alternating dual-task conditions. In each trial, a tone, either low- or high-pitched, was presented at one of the three/six keys and participants had to indicate either the pitch of the tone (extraneous dual task) or the key with which the tone was presented (skill-focused dual task) after finishing the execution of the motor sequence. Motor task performance was assessed by reaction time (RT) and movement duration (MD). The results reveal that in RT performance, there was an advantage for the preparation and initiation of motor sequences in the skill-focused dual-task condition at the beginning of practice. With practice, this advantage decreased and the gap between RTs under the two different conditions decreased. The MDs under the skill-focused dual-task condition were generally slower than those under the extraneous dual-task condition across practice. These results show that the effects of attentional direction differ not only as a function of the amount of practice but also as a function of the stage of information processing. Furthermore, the results indicate that the direction of attention alone does not explain the different patterns of performance at different skill levels seen across dual-task studies; rather, the skill levels, the nature of cognitive demands, the difficulty level of dual tasks, and the complexity of the motor skill could all drive performance difference.

The study and the article were mainly conducted, executed, analyzed, and written by the first author. Substantial support from co-authors was appreciated. The article was submitted in April 2020 and was accepted in September 2020 by the Journal of Motor Behavior. It is an international, peer-reviewed scholarly journal dedicated to the advancement of scientific research in the field of motor control mechanisms.

Journal of Motor Behavior, 2020

ARTICLE

The Varying Effects of Dual Tasks on the Performance of Motor Skills across Practice

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ABSTRACT. Numerous previous studies using the dual-task methodology have indicated that the effect of attentional direction on the performance of motor skill differs as a function of skill levels. Whereas previous studies relied mostly on inter-individual comparisons, this study focused on how the effects of different attentional conditions change within individuals with practice. Participants were instructed to learn a short and a long keying sequence (three versus six keys) and then practiced under two block-wise alternating dual-task conditions. In each trial, a tone, either low- or high-pitched, was presented at one of the three/six keys and participants had to indicate either the pitch of the tone (extraneous dual task) or the key with which the tone was presented (skill-focused dual task) after finishing the execution of the keying sequence. Motor task performance was assessed by reaction time (RT) and movement duration (MD), and the concurrent cognitive task performance was assessed by the error rate. RT was faster in the skill-focused dual-task condition at the beginning of practice, whereas a generally shorter MD was found in the extraneous dual-task condition. The error rate in the extraneous dual task decreased with practice, whereas in the skill-focused dual task, it increased with practice. These results show that the effects of attentional direction differ not only as a function of the amount of practice but also as a function of the stage of information processing. Furthermore, our results indicate that the direction of attention alone does not explain the different patterns of performance at different skill levels seen across dual-task studies; rather, the skill levels, the nature of cognitive demands, the difficulty level of dual tasks, and the complexity of the motor skill could all drive performance differences.

Keywords: Keying sequence, dual task, reaction time, movement duration, interkey interval

Introduction

Research has consistently found differences in the attentional demands required for motor skill execution inter-individually between novices and experts or intra-individually between newly acquired and well-learned motor skills (e.g., Beilock et al., 2002; 2004; Leavitt, 1979; Smith & Chamberlin, 1992; Vuillerme & Nougier, 2004). Fitts and Posner (1967) and Anderson (1982) proposed that low-skilled performers need to keep declarative knowledge about motor skill execution in working memory and attend to the components of motor skill execution in a step-by-step fashion. On the other hand, highly skilled performers use procedural knowledge, which does not require the same level of attention, to drive motor skill execution, which thus becomes automatic (Anderson, 1982; Fitts & Posner, 1967). Procedural knowledge develops with increasing practice, and all components of execution are encoded and proceduralized together, supporting a shift as a result of practice from consciously controlled to more automatic skill execution (Abernethy et al., 2007). The differences in attentional demands of motor skill execution have led to research investigating how situations that direct the focus of attention—either by directing attention toward execution or by shifting attention away from execution—affect performance across levels of expertise. However, most previous studies have focused on how the effects of different attentional focus conditions differ between individuals, usually comparing novices and experts (e.g., Beilock et al., 2002; 2004; Beilock & Gray, 2012; Castaneda & Gray, 2007; Gray, 2004). Few studies have examined how the effects of different attentional conditions change within individual with practice.

To assess the degree of automaticity in performing a motor skill and the attentional demands for motor skill execution, previous studies have employed a "dual-task methodology" (Abernethy, 1988; Gabbett et al., 2011; Gabbett & Abernethy, 2013; Leavitt, 1979; Schneider & Shiffrin, 1977). This term refers to experiments in which participants are required to perform both a primary task related to the motor skill and a concurrent task, generally cognitive in nature. The theoretical assumption underlying numerous dual-task studies is that attentional resources are limited, the need to share them between the two tasks can result in the cognitive-motor interference (Koch et al., 2018; Schaefer, 2014). The cognitive-motor interference refers to a deterioration of motor or cognitive task performance when two tasks are performed at the same time (Al-Yahya et al., 2011; Patel et al., 2014). Expertise level is an important factor that affects the cognitive-motor dual-task situations (Schaefer, 2014). Novices normally show cognitive-motor interference in dual-task conditions (e.g., Leavitt, 1979; Schaefer & Scornaienchi, 2020). In contrast, people who are experts in the motor skill usually show little performance

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decrement in dual-task condition (e.g., Leavitt, 1979; Schaefer & Scornaienchi, 2020).

Not only expertise influences the effect of a concurrent cognitive task on the performance of the motor task, but also the focus of attention the concurrent cognitive task induces (e.g., Beilock et al., 2002; 2004; Beilock & Gray, 2012; Gray, 2004; Jackson et al., 2006). To induce an extraneous focus, concurrent cognitive tasks can include counting backwards (Nicolson & Fawcett, 1990), detecting auditory probes (Abernethy, 1988), and tone counting (Nissen & Bullemer, 1987). Other concurrent cognitive tasks are thought to induce a skill-focused, internal focus of attention toward execution. In this type of task, participants are asked to explicitly report a particular part of the motor skill execution according to a stimulus. For example, in a soccer dribbling task, participants were asked to identify which side of their foot was touching the ball when they heard a tone sound; in a baseball-batting task, participants had to identify the direction of the bat when a tone was played (Beilock et al., 2002; Gray, 2004).

Previous studies have found that the effects of attentional direction, as manipulated by dual tasks, on the performance of motor skills differ as a function of skill level. Novices have shown better performance in a skill-focused than in an extraneous dual-task condition (Beilock et al., 2002; 2004; Gray, 2004). It has been argued that to novices' performance a skill-focused dual task was not disruptive because novices were executing the task consciously in a step-by-step manner and were already attending to each action step (Anderson, 1983; Beilock & Gray, 2012; Fitts & Posner, 1967; Proctor & Dutta, 1995). On the other hand, novice performance was impaired in an extraneous dual-task condition because novices had to attend to extraneous sensory information during motor skill execution resulting in insufficient resources available for motor skill execution (Beilock et al., 2002; Gray, 2004; Nissen & Bullemer, 1987). However, experts generally perform better in an extraneous dual-task condition than in a skill-focused dual-task condition. It has been argued that the extraneous stimulus of the concurrent cognitive task does not greatly impair performance of experts, because their motor skill execution has become automatic and requires little attention (Anderson, 1993; Castaneda & Gray, 2007; Fitts & Posner, 1967; Gray, 2004). Consequently, they can direct most of their attention to processing the concurrent cognitive task (Beilock et al., 2002). In contrast, experts' performance is impaired when a skill-focused dual task is introduced, perhaps because this added task forces them to monitor the process of execution, which leads to the breaking down of automatic mechanisms (Beilock & Carr, 2001). Experts in this situation are believed to reinvest in the step-by-step controlling process using declarative knowledge (Masters et al., 1993; 2008).

Despite this evidence of differences in the attentional demands of motor skill execution, some weaknesses in prior research can be identified. First, existing inferences are based mostly on inter-individual comparisons between individuals at different skill levels of the motor skill involved. The differences between individuals at different skill levels may thus reflect (at least in part) previously existing inter-subject differences, such as differences in general performance, preferences for different attentional foci, or different working memory capacities. Even where intra-individual comparisons have been made, the change in processes across practice, detection of which would require a longitudinal approach, has never been investigated. Second, studies thus far have looked mostly at effects on performance outcomes (such as the time required to complete a slalom course), and to some extent at effects on movement execution (Beilock et al., 2002; Jackson et al., 2006), but not at effects on information processing. If a simple information-processing stage model of motor skill is assumed, at least a selection/initiation stage and an execution stage can be distinguished (Dudman & Krakauer, 2016; Kunde et al., 2004). To execute a motor task, a person is first required to select and initiate the proper movement sequence which is then executed. The efficacy of information processing involved at these two stages could influence the performance of the motor skill, and the effect of attention directions might differ not only as a function of the amount of practice but also depending on the stage of information processing.

The aim of this study was to examine how the effects of two kinds of dual tasks (skill-focused versus extraneous) on the performance of a motor skill change with practice, by using a dual-task methodology within an intra-individual design. To this end, we adapted a keying sequence task paradigm (Stöcker & Hoffmann, 2004) and a dual-task paradigm (Gray, 2004). We chose to use the keying sequence task paradigm because keying sequences are considered the building blocks of more hierarchically controlled and complex motor skills (Rhodes et al., 2004). The performance of keying sequences can be improved in a relatively short period of time. Furthermore, the time and accuracy of individual key presses can be registered precisely, enabling researchers to dissect the different phases of processing and trace the underlying control processes (Rhodes et al., 2004).

In our study, participants were instructed to learn and then explicitly practice two fixed keying sequences (a three-key and a six-key sequence) in a discrete sequence production task. During the practice of the two sequences, a tone was presented randomly at one of the key presses during each execution of the keying sequence.

As a concurrent cognitive task, participants had to indicate, after executing the keying sequence, either the pitch of the tone (in the extraneous dual-task condition) or the key at which the tone was presented (in the skill-focused dual-task condition). We monitored the participants' performance of the key sequences to find out how the effects of dual tasks change with practice. We used reaction time (RT, also known as initiation time or first-response time) and movement duration (MD, also known as movement time) as indicators of the performance of the keying sequences. RT refers to the time needed to select and initiate a keying sequence execution; MD refers to the amount of time needed to actually execute a keying sequence. Based on the results of previous studies using the dual-task paradigm, we predicted that at the beginning of practice, the MD of participants in the skill-focused dual-task condition (location in the sequence) would be faster than those of participants in the extraneous dual-task condition (pitch) (Beilock et al., 2002). However, we anticipated that with practice or experience, the gap between these two conditions would decrease and eventually be eliminated; in fact, we expected that with sufficient practice, MD would be faster in the extraneous dual-task condition (Beilock et al., 2002; Jackson et al., 2006). However, because the selection/initiation stage of motor skill is a new construct within the literature using the dual-task methodology, the analyses of RT were exploratory without specific predictions made a priori.

In addition, to further explore the underlying control processes of the execution, we also investigated the effect of tone location on interkey intervals (IKIs) in different dual-task conditions. IKI refers to each interval between two contiguous key presses within the execution of a keying sequence. We compared IKIs relative to tone location between skill-focused and extraneous dual-task conditions in both early and late blocks of practice.

Finally, we also investigated performance of the concurrent cognitive task and how it changed with practice. Based on the results of previous inter-individual studies on the performance of concurrent cognitive tasks, we expected that the error rate in the extraneous dual task would decrease with practice, whereas the error rate in the skill-focused dual task would increase with practice.

Methods

Participants

Thirty-two healthy undergraduate and graduate students (18 male, 14 female) were recruited for this study. All participants were between the ages of 20 and 30 ($M = 23.9$, $SD = 2.5$) and had never experienced a similar keying sequence experiment. They were offered extra credit for their participation and were informed that the experiment was about the effects of different conditions on the execution of keying sequences. Informed consent was obtained prior to the experiment. For reasons explained below, data of two male participants were eliminated.

Apparatus

We used MATLAB 2017b, PsychToolbox-3 for stimulus presentation and data collection. The program ran on a PC (FUJITSU DTF, Intel (R) Core (TM) i7-7700, 3.60 GHz CPU, 16 GB RAM, 64-bit Windows 10). The stimuli were presented to the participants on a 17-inch Dell E1715S monitor. The monitor was black, located approximately 50 cm in front of the participants; the instructions were in white 16-point Arial font. The spatial resolution of the monitor was set at 1024 × 768. Tones were presented via two loudspeakers (Logitech Speaker System Z520) located approximately 20 cm bilaterally away from the monitor.

One response board was used during this study. The hardware was constructed from two disassembled "Black Box Toolkit" four-button response pads that enabled the precise recording of timing. The response pads were mounted as eight response keys and configured on a horizontal line similar to the layout of a commercial keyboard. The eight response keys were labeled with eight letters A, S, D, F, G, H, J, and K, in that order. The response board functions like a computer keyboard but has fewer buttons and can measure the response time of participants with a millisecond resolution, making it a better tool for recording rapid responses by participants than a computer keyboard (Plant et al., 2004). Throughout the experiment, participants rested their left index, middle, ring, and little fingers on the F, D, S, and A keys, respectively, and their right index, middle, ring, and little fingers on the G, H, J, and K keys, respectively.

Procedure

The main task of this study was to learn and perform two different bimanual keying sequences of three and six keys, respectively. The experiment followed the design of a previous study (Stöcker & Hoffmann, 2004) and consisted of three phases, as described below.

Phase 1: Familiarizing with the response board

The purpose of practice in Phase 1 was to familiarize participants with the response board. In each trial, one of six letters (S, D, F, G, H, or J) in white 16-point Arial font was randomly presented at the center of the monitor. Participants were asked to press the response key corresponding to the letter as quickly as possible. When participants pressed the correct key, the next trial then started with the presentation of the next letter stimulus after a response-to-stimulus interval (RSI) of 800 ms.

When participants pressed a wrong response key, the word ‘‘Error’’ in red 16-point “Arial” font was presented at the center of the monitor for 700 ms. Then, the next trial started after an RSI of 800 ms. Each participant was asked to complete two blocks of 60 trials. There was a 5-second break between blocks. No data were recorded in Phase 1.

Phase 2: Memorizing keying sequences

In Phase 2, participants had to learn one short and one long keying sequence, which they were to perform in response to a one-letter cue (X or Y) for each sequence. The short sequence, labeled “X,” consisted of three ordered letters (G-S-H); the long sequence, labeled “Y,” had six ordered letters (S-G-F-H-D-J). Each trial started with a white fixation cross presented for 1,500 ms at the center of the monitor. Then the sequence cue (X or Y) was displayed in the upper half of the monitor (white, 60-point Arial) and remained throughout the sequence. Simultaneously, the first letter of the sequence was presented (white, 16-point Arial) at the center of the screen until a key was pressed; participants were asked to press the corresponding key. The next letter of the sequence was displayed after an RSI of 800 ms. The RSI was used to prevent participants from practicing fast sequence execution during Phase 2 and to enable participants to build up only central-symbolic representations of the two sequences (Stöcker & Hoffmann, 2004). If an incorrect key was pressed, the word ‘‘Error’’ appeared at the bottom of the screen for 700 ms (red, 16-point Arial). If the error was not on the last letter of its sequence, the next letter of the sequence was displayed after an RSI of 800 ms. After the whole sequence was completed, the sequence cue disappeared and the fixation cross reappeared for 1,500 ms.

Phase 2 consisted of two blocks of 60 trials each (30 on X and 30 on Y, presented in random order). At the end of each block, the error rate for that block was shown on the monitor for 5 s.

Phase 3: Performing under dual-task conditions

In each trial, after the presentation of a fixation cross at the center of the monitor for 1,500 ms, only the sequence cue (X or Y) was presented in the upper half of the monitor (red, 60-point Arial). Key-specific letters were not presented during this phase. Participants were asked to immediately initiate the respective sequence. They were informed that the primary goal of the task was to press the whole corresponding sequence as fast as possible without making mistakes, and that they should begin as soon as the sequence cue appeared on the monitor.

This phase used a previously described dual-task methodology (Gray, 2004) that was modified for the keying sequence. An 80-ms tone was presented during each trial, at some point after the participants had started the trials by pressing the first key of the sequence. This tone onset concurred with the onset of one response in the three or six keying sequence; it could be either low-pitched (250 Hz) or high-pitched (500 Hz). The key at which the tone co-occurred and the pitch frequency were randomly selected from among the three or six keys and the two frequencies, but with an equal distribution to prevent the participants from prejudging the tone to be presented. In the extraneous dual-task condition, participants were instructed to monitor the tone carefully to distinguish whether it was low or high in frequency. In each trial, after finishing the keying sequence, the participants were required to indicate the pitch of the tone by pressing a corresponding key (A for low and K for high). In the skill-focused dual-task condition, participants were asked to monitor which keystroke was accompanied by a tone. In each trial, after finishing the keying sequence, they were required to indicate at which keystroke the tone was presented by pressing the corresponding key (S, D, F, G, H, or J). After participants had answered the question about the concurrent cognitive task, the fixation cross reappeared for 1,500 ms. When a wrong key was pressed during the execution of the keying sequence, the sequence trial was broken off, and the word “Error” was shown (in red 16-point Arial) at the center of the screen for 700 ms. Then, the next sequence trial commenced, and the next sequence cue was displayed after a 1500 ms presentation of the fixation cross.

Each participant performed 16 blocks in Phase 3, including 8 in each dual-task condition. Each block had 12 “X” sequence trials and 12 “Y” sequence trials, presented in random order. At the end of each block, the error rate and the mean RT of the execution of the keying sequence for that block were shown on the screen. Each block was followed by a short break (5 s), with longer breaks (30 s) after blocks 4, 8, and 12. The dual-task condition blocks were repeated in an alternating pattern for each participant, and the order of the dual-task blocks was counterbalanced across participants.

Data Processing

Only trials in Phase 3 in which participants completed the whole sequence of keystrokes with no errors were used for data analysis. Two male participants were dropped from the data analysis. One was eliminated because he misunderstood the protocol for the extraneous dual-task condition and chose the same key to answer the question from the concurrent cognitive task in every extraneous dual-task trial. The other participant was removed from the analysis because he produced a faulty sequence in each trial within 4 of 16 blocks (two extraneous and two skill-focused).

For each participant, RT and IKIs of each trial in Phase 3 were measured. RT was defined as the time between the onset of the stimulus presentation and the initial key press. IKI was defined as the interval between two contiguous key presses, as measured from the onset of one key press to the onset of the next. Thus, in an X trial, two IKIs within the three-key sequence were recorded and indicated by T_2 and T_3, respectively; in a Y trial, five IKIs were recorded and indicated by T_2, T_3, T_4, T_5, and T_6, respectively. MD was defined as the sum of the IKIs (two in each X trial and five in each Y trial). Sequences were considered erroneous if they included a wrong key press, or if RTs or MDs exceeded the grand mean across all the same sequences in the respective block for that participant by three or more standard deviations. After elimination of erroneous sequences, 93.0% of the X sequence trials and 90.0% of the Y sequence trials remained.

To investigate in detail the underlying control processes of keying sequences, we categorized the IKIs as a function of their position relative to the key at which the tone was presented. In this analysis, all IKIs preceding the response onset with which the tone presentation concurred were classified in the Location -1 category. IKIs of the key press with which the tone was presented were categorized as Location 0, and the subsequent IKIs were classified into Locations 1 to 5 according to their position relative to the key at which the tone was presented. For example, if the tone was presented at the fourth key press of a six-key sequence, T_2 and T_3 were included in Location -1, whereas T_4, T_5 and T_6 were classified into Locations 0, 1, and 2, respectively. For each participant, the separately classified IKIs in early blocks (Blocks 1–4) and late blocks (Blocks 5–8) were then averaged separately. The mean IKIs for the short sequence in each category were indicated as L_{-1} to L_2, and the mean IKIs for the long sequence were indicated as L_{-1} to L_5.

The concurrent cognitive task performance was measured as error rates of the dual task (either extraneous or skill-focused). For each block, the error rate was measured as the percentage of wrong responses recorded. Wrong responses were defined as falsely detecting the tone frequency (low or high) or the key at which the tone was presented (S, D, F, G, H, or J).

Statistical Analysis

The mean RT and the mean MD per participant, block, and dual-task condition were analyzed with 2 (sequence: three-key vs. six-key) × 2 (dual task: skill-focused vs. extraneous) × 8 (block) analyses of variance (ANOVAs) with repeated measurement.

For the IKIs data, because of the different sequence lengths, the IKIs were analyzed separately for the two sequences. In this analysis, IKIs related to tone presentation were averaged per participant, early (Blocks 1–4) versus late blocks (Blocks 5–8), dual-task condition, and location category, then analyzed with a 2 (dual task) × 2 (phase: early blocks or late blocks) × 4 or 7 (location: L_{-1}–L_2 or L_{-1}–L_5) ANOVA with repeated measurement. Planed comparisons were carried out to examine the difference between IKIs related to tone position for each combination of phase and dual task and the difference between dual-task conditions for each combination of phase and location.

Error rates in the concurrent cognitive tasks were arcsine-transformed to correct for skewness (Stöcker & Hoffmann, 2004; Winer et al., 1991). The arcsine-transformed error rates were analyzed with a 2 (sequence) × 2 (dual task) × 8 (block) ANOVA with repeated measurement. Separate ANOVAs for the two dual-task conditions with sequence, and block as factors were conducted for further analysis when a significant dual task × block interaction was found.

The Greenhouse–Geisser correction was used to adjust degrees of freedom if the sphericity assumption was violated. Effect sizes (f) are reported for all analyses (f effect sizes of 0.10, 0.25, and 0.40 are small, medium, and large, respectively; Cohen, 1988). Estimated marginal means and differences between estimated marginal means were computed to describe main effects and interaction effects.

Results

Reaction Time

The ANOVA showed a main effect of block, $F(2.00, 57.99) = 66.75$, $p < .001$, $f = 1.52$, indicating that RTs decreased with practice (see Figure 1). Also a main effect of sequence, $F(1, 29) = 11.12$, $p = .002$, $f = 0.62$, was found showing that the RTs in the three-key sequence ($M = 692$ ms) were shorter than RTs in the six-key sequence ($M = 758$ ms). The dual task × block interaction indicated that RTs in the skill-focused dual-task condition would initially be faster than RTs in the extraneous dual-task condition and that the difference would decrease with practice, $F(1.93, 55.94) = 3.51$, $p = .038$, $f = 0.36$ (see Figure 1). This interaction did not differ for the two sequences, sequence × dual task × block, $F(3.85, 111.68) = 0.93$, $p = .49$. The sequence × block interaction was significant, $F(4.38, 126.95) = 2.61$, $p = .034$, $f = 0.30$), indicating that the sequence-length effect gradually decreased with practice (the differences between estimated marginal means for sequences across practice were 124, 86, 67, 89, 62, 43, 36 and 28 ms for Block 1-8, respectively). Neither the main effect of dual task, $F(1, 29) = 3.69$, $p = .065$, nor the interaction of sequence × dual task was significant, $F(1, 29) = 0.71$, $p > .40$.

Movement Duration

The ANOVA showed a significant main effect of dual task, $F(1, 29) = 55.41$, $p < .001$, $f = 1.36$, and a

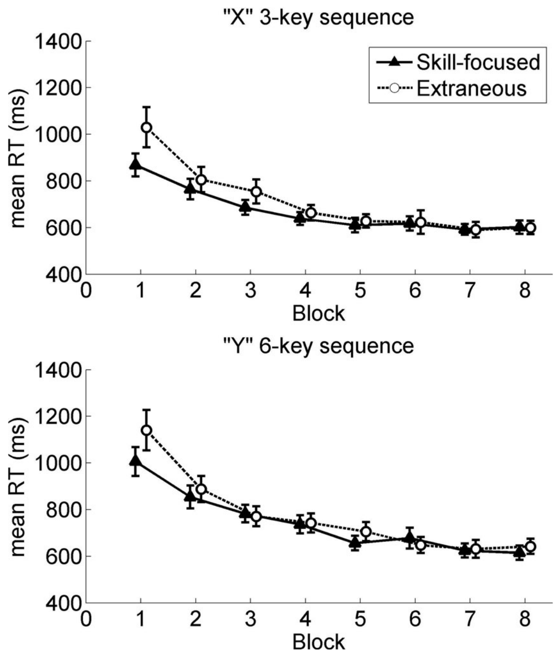

FIGURE 1. Reaction time in the two dual-task conditions during practice. Error bars represent standard errors.

significant main effect of sequence, $F(1, 29) = 124.34$, $p < .001$, $f = 2.06$, showing that the MD was shorter in the extraneous dual-task condition (extraneous dual-task condition: $M = 902$; skill-focused dual-task condition: $M = 1037$ ms) and that it was shorter in the three-key ($M = 472$ ms) than in the six-key sequence ($M = 1467$ ms). A significant dual task × sequence interaction indicated that the difference in MD between the two dual-task conditions was larger in the six-key sequence (extraneous dual-task condition: $M = 1367$ ms; skill-focused dual-task condition: $M = 1568$ ms) than three-key sequence (extraneous dual-task condition: $M = 438$; skill-focused dual-task condition: $M = 507$ ms), $F(1, 29) = 28.50$, $p < .001$, $f = 0.99$. It also showed a significant main effect of block, $F(1.72, 49.91) = 44.90$, $p < .001$, $f = 1.74$, indicating that the MD decreased with practice. The significant sequence × block interaction, $F(2.14, 62.09) = 56.43$, $p < .001$, $f = 1.40$, indicates that the effect of sequence length decreased gradually with practice (the differences between estimated marginal means for sequences across practice were 1563, 1159, 1033, 994, 884, 820, 747 and 759 ms for Block 1-8, respectively). The dual task × block interaction did not attain statistical significance, $F(2.12, 61.36) = 0.35$, $p = .72$, implying that the MD in the extraneous dual-task condition was generally shorter than the MD in the skill-focused dual-task condition across practice. The three-way interaction did not approach significance, $F(2.64, 76.45) = 0.67$, $p = .60$ (see Figure 2).

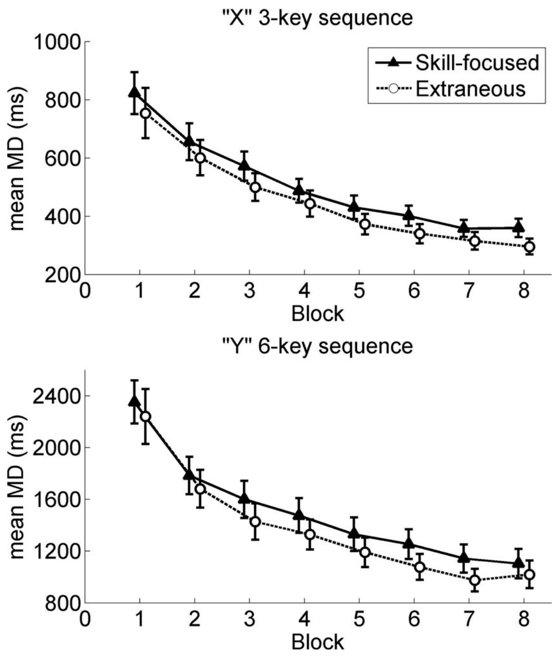

FIGURE 2. Movement duration in the two dual-task conditions during practice. Error bars represent standard errors.

Effect of Tone on Interkey Intervals

For the three-key sequence, in addition to significant main effects of phase, $F(1, 29) = 68.81$, $p < .001$, $f = 1.54$, and dual task $F(1, 29) = 36.34$, $p < .001$, $f = 1.12$, the significant main effect of location indicated that the IKI differed as a function of its position relative to the key at which the tone was presented, $F(2.30, 66.60) = 9.55$, $p < .001$, $f = 0.57$ (258 ms for L_1, 236 ms or less for all other locations). Furthermore, the ANOVA showed that the effect of location decreased with practice, based on the main effect of phase × location, $F(2.26, 65.59) = 6.30$, $p = .002$, $f = 0.47$ (early blocks: 290, 284, 320, and 283 ms for location L_{-1}–L_2, respectively; late blocks: 173, 180, 195, and 188 ms for location L_{-1}–L_2, respectively). The effect of dual task differed across the IKIs relative to the location of the tone presented: dual task × location, $F(2.07, 59.97) = 12.40$, $p < .001$, $f = 0.65$. This indicated that the difference between the skill-focused and extraneous dual-task conditions was larger at L_1 than at other locations (61 ms for L_1, 34 ms or less at all other locations).

Planed comparisons showed that in the skill-focused dual-task condition, L_1 was slower than L_{-1}, L_0, and L_2 (which means longer IKI for L_1) in both early and late

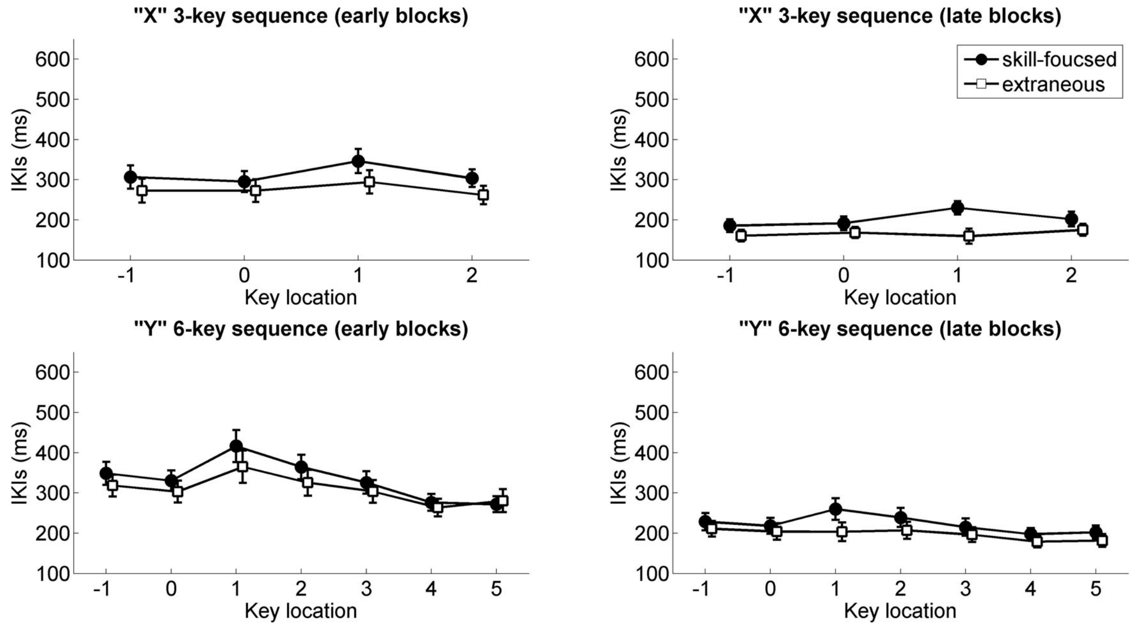

FIGURE 3. Interkey intervals as a function of their location relative to the key at which the tone was presented, for both sequences and in the two dual-task conditions during practice. Error bars represent standard errors.

blocks (ps < .002; early blocks: 307, 295, 346, and 304 ms for location L_{-1}–L_2, respectively; late blocks: 186, 191, 230, and 202 ms for location L_{-1}–L_2, respectively). However, in the extraneous dual-task condition, L_1 was slower than $L_{-1}L_0L_2$ in early blocks (ps < .013; 273, 273, 294, and 262 ms for location L_{-1}–L_2, respectively) but not in late blocks (ps > .24, 161,168, 165, and 170 ms for location L_{-1}–L_2, respectively). Moreover, for both phases, the IKI at each location was longer in the skill-focused dual-task condition than in the extraneous dual-task condition (ps < .038).

A similar result was found for the six-key sequence. In addition to significant main effects for phase, dual task, and location [respectively, $F(1, 29) = 105.96$, $p < .001$, $f = 1.91$, $F(1, 29) = 23.44$, $p < .001$, $f = 0.90$, and $F(1.64, 47.57) = 15.11$, $p < .001$, $f = 0.72$], the ANOVA revealed a significant dual task × location interaction, $F(4.04, 117.11) = 5.69$, $p < .001$, $f = 0.44$ (the differences between the two dual-task conditions were 64 ms for L_1 and 36 ms or less for all other locations). The ANOVA furthermore showed that the effect of location decreased with practice: phase × location, $F(2.98, 86.33) = 14.18$, $p < .001$, $f = 0.70$ (early blocks: 334, 317, 391, 345, 315, 270, and 276 ms for location L_{-1}–L_5, respectively; late blocks: 220, 211, 232, 223, 206, 188 and 192 ms for location L_{-1}–L_5, respectively).

Planned comparisons showed that L_1 was slower than $L_{-1}, L_0, L_2, L_3, L_4$, and L_5 in both early and late blocks in the skill-focused dual-task condition (ps < .002; early blocks: 349, 330, 416, 364, 326, 276 and 272 ms for location L_{-1}–L_5, respectively; late blocks: 229, 218, 260, 239, 215, 198 and 202 ms for location L_{-1}–L_5, respectively). However, under the extraneous dual-task condition, L_1 was slower than $L_{-1}, L_0, L_2, L_3, L_4$, and L_5 only in early blocks (ps < .008; 318, 303, 365, 325, 304, 264 and 281 ms for location L_{-1}–L_5, respectively). In late blocks, L_1 was not slower than $L_{-1}, L_0, L_2, L_3, L_4$, and L_5 (ps > .09; 211, 204, 204, 207, 196, 182 and 185 ms for location L_{-1}–L_5, respectively). Next, planned comparisons showed that in early blocks, only L_{-1} through L_2 in the skill-focused dual-task condition were longer than in the extraneous dual-task condition (ps < .026). In late blocks, the IKI at each location was longer in the skill-focused dual-task condition than in the extraneous dual-task condition (ps < .012; see Figure 3).

Concurrent Cognitive Task Performance

The ANOVA showed that error rates were higher in six-key sequence trials ($M = 13.1\%$) than in three-key ones ($M = 8.3\%$), $F(1, 29) = 13.02$, $p = .001$, $f = 0.67$. Tone identification ($M = 18.9\%$) was generally more accurate than key identification ($M = 2.5\%$), as indicated by the main effect of dual task, $F(1, 29) = 39.27$, $p < .001$, $f = 1.16$. The block effect, $F(4.38, 126.93) = 3.25$, $p = .012$, $f = 0.34$, differed between the two dual-task

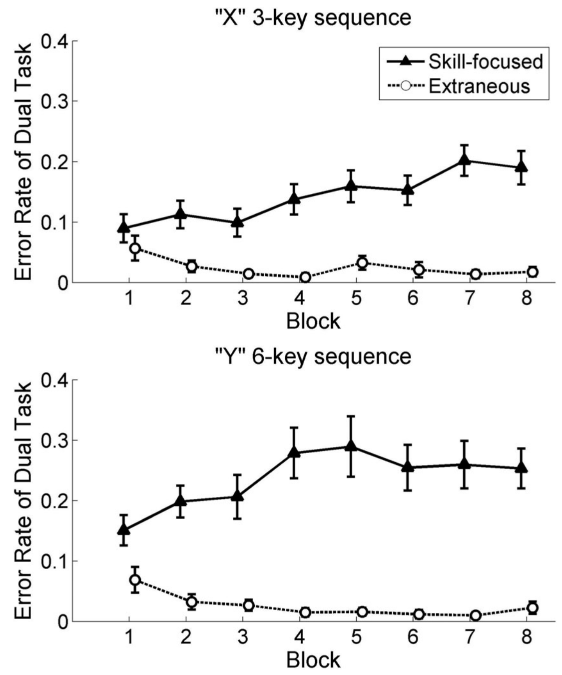

FIGURE 4. Performance of concurrent cognitive tasks in the two dual-task conditions during practice. Error bars represent standard errors.

conditions, dual task × block interaction, $F(4.06,\ 117.34) = 9.29$, $p < .001$, $f = 0.57$. Additional ANOVAs revealed that the error rate in the concurrent cognitive task significantly decreased with practice in the extraneous dual-task condition (6.3%, 2.9%, 2.0%, 1.2%, 2.4%, 1.6%, 1.2% and 2.0% ms for Block 1-8, respectively), $F(2.63,\ 76.17) = 4.78$, $p = .006$, $f = 0.40$, and significantly increased with practice in the skill-focused dual-task condition, $F(3.94,\ 114.16) = 6.62$, $p < .001$, $f = 0.48$ (12.0%, 15.5%, 15.2%, 20.8%, 22.4%, 20.3%, 23.1% and 22.1% ms for Block 1-8, respectively; see Figure 4).

Discussion

Previous studies using the dual-task methodology suggested the existence of differences between individuals at different skill levels in the influence of attentional direction on the performance of motor skills (Beilock et al., 2002; 2004; Castaneda & Gray, 2007; Diekfuss et al., 2017; Gray, 2004). To understand how the effects of different attentional conditions change as a function of practice, the present study examined the performance of keying sequences under two different dual-task conditions across practice, applying a longitudinal, intra-individual approach. By assessing different components of skill performance (RT and MD), we also addressed whether different stages of motor skill are affected differently. To investigate the underlying control processes and reveal the focus of attention, we further explored the effect of tone location on IKIs and the performance of the concurrent cognitive task in different dual-task conditions, respectively.

Regarding the selection and initiation of the motor skill, the analysis of RT showed that, at the beginning of practice, participants could more rapidly select and/or initiate the keying sequence in the skill-focused dual-task condition than in the extraneous dual-task condition. However, with practice, the benefit of skill-focused attention for selecting and/or initiating the keying sequence diminished. This finding is in line with the idea that, at the beginning of practice, the control of the keying sequence was based on declarative knowledge (i.e. explicit knowledge) of the keying sequences (e.g., "the serial letters of the keying sequence") and consciously attended to in real-time (Anderson, 1982, 1983; Beilock & Gray, 2012; Fitts & Posner, 1967). Participants selected the keying sequence to respond to a sequence label stimulus by searching and retrieving the explicit knowledge of the keying sequence from memory (Beilock & Gray, 2012). This search and retrieval processes required working memory engagement (Thompson, 2013). In dual-task situations, participants have to keep both tasks ready in working memory (Koch et al., 2018). Maintaining the requirement of paying attention to keying sequence execution in the working memory might require less effort and demand less cognitive resources than maintaining the requirement of paying attention to an extraneous stimulus during the early practice, because the former fitted their natural inclination of the attentional direction (Marchant et al., 2009). Therefore, the searching and retrieving of explicit knowledge of keying sequences appears to have been faster in the skill-focused dual-task condition on account of more cognitive resources available.

Gradually, with practice, explicit knowledge of the keying sequence became part of the cognitive representation of the corresponding sequence label (Thompson, 2013). In this case, the keying sequence was selected in the context without requiring further cognitive processing and working memory. Therefore, the keying sequence selection was not influenced by the dual-task conditions. Moreover, proficiency in a motor skill (in this case, pressing a keying sequence) increases with practice, and the underlying control processes change (Anderson, 1982, 1983; Beilock et al., 2002; Fitts & Posner, 1967; Gray, 2004). The keying sequence execution in the extraneous dual-task condition was relatively automatic, compared to the skill-focused dual-task condition (Beilock & Gray, 2012), which will be discussed in detail in subsequent paragraphs. The more automatic the motor skill execution is, the less time is required for motor skill initiation (Ille et al., 2013). Thus, the high degree of automaticity of the keying sequence execution enabled a fast keying sequence initiation in the extraneous dual-task condition in late blocks.

Looking at the execution of the motor skill, the analysis of MD showed a generally detrimental effect of directing participants' attention to motor skill execution, which does not align with the results of previous studies using the dual-task methodology (e.g., Beilock et al., 2002; 2004; Gray, 2004). These findings could, however, be tentatively interpreted in terms of the cognitive involvement demands and difficulty level of our concurrent cognitive tasks. Diekfuss et al. (2017) reported that in a shooting task, regardless of the level of participants, performance was significantly better in the extraneous dual-task condition than in the skill-focused dual-task condition, in line with our results. In the study by Diekfuss et al. (2017), the NASA-Task Load Index was administered upon completion of each condition to measure workload associated with the different conditions. Diekfuss and colleagues (2017) showed that workload was significantly lower in the extraneous dual-task condition compared to the skill-focused dual-task condition, and the causal relationship between skill level and performance was partially mediated by the workload level in both dual-task conditions. They concluded that the effect of dual-task conditions would be driven by the workload demands of the concurrent cognitive tasks used to direct attention (Diekfuss et al., 2017). Therefore, the reason for the generally negative effects of the skill-focused dual task on motor skill execution might be the different cognitive resource demands of the concurrent cognitive tasks used in the present study.

At the beginning of practice, which required execution of the keying sequence on the basis of declarative knowledge about the sequence, performance in both conditions suffered from the presence of the concurrent cognitive task and its cognitive involvement demands (Beilock et al., 2002; 2004; Gray, 2004; Schaefer, 2014). Therefore, the IKIs at L_1, which was the first key press after the tone presentation, were considerably slower than the IKIs at other locations. In the skill-focused dual-task condition, the concurrent cognitive task was related to the execution of the keying sequence (Beilock et al., 2002; 2004; Diekfuss et al., 2017; Gray, 2004). Participants needed to monitor each key press and focus on motor skill execution to judge whether a tone was presented with the key press. This conscious type of motor control requires additional cognitive involvement related to the dual task while pressing each key before the presentation of the tone. Conversely, in the extraneous dual-task condition, the cognitive involvement was partly or completely allocated to tone identification, which is not related to the movement (Beilock et al., 2002; 2004; Diekfuss et al., 2017; Gray, 2004). Participants simply needed to identify the tone frequency whenever they heard a tone; there were no cognitive demands related to the dual task before the presentation of the tone. As a result, the IKIs before tone presentation were slower in the skill-focused dual-task condition than in the extraneous dual-task condition, leading to slower execution in the former condition in early blocks.

With increasing amounts of practice, the development of procedural knowledge, which encodes and proceduralizes successive movements together, reduces the attentional demands and cognitive involvement required to execute keying sequences and leads to decreased dual-task interference in the extraneous dual-task condition (Anderson, 1982; Beilock et al., 2002; Gray, 2004; Jackson et al., 2006; Keele & Summers, 1976; Schaefer, 2014). Our results showed that in the extraneous dual-task condition, the IKIs at L_1 were not slower than the IKIs at other locations. We would suggest that, after substantial practice, the keying sequence could be executed automatically (Anderson, 1982; Fitts & Posner, 1967). By this point, the execution of the keying sequence would be interrupted only mildly by the need to allocate attentional resources to the extraneous dual task (Beilock et al., 2002; Gray, 2004; Leavitt, 1979; Smith & Chamberlin, 1992; Vuillerme & Nougier, 2004). In contrast, the skill-focused dual task requires slow execution to decide at which key the tone was presented. This finding seems consistent with other studies, which found that a skill focus disrupts well-learned or proceduralized performances, leading to a breakdown of skilled performance and error-prone step-by-step execution of the motor task (Kimble & Perlmuter, 1970; Langer & Imber,1979; Lewis & Linder, 1997; Masters, 1992). Once skilled performance has broken down, each component of motor skill must be activated and run separately, which still requires cognitive involvement (Masters, 1992, 1993). Therefore, the execution of the keying sequence was still interrupted considerably by the skill-focused dual task. As a result, in the skill-focused dual-task condition, in late blocks the IKIs at L_1 were still slower than IKIs at other locations. Moreover, the conscious step-by-step control of execution was less efficient (Beilock & Carr, 2001; Kimble & Perlmuter, 1970; Langer & Imber,1979; Lewis & Linder, 1997). Our results showed that IKI at each location in the skill-focused dual-task condition was longer than that in the extraneous dual-task condition in late blocks, leading to slower execution in the former condition in late blocks. We can thus conclude that the execution of keying sequences is slowed significantly by the skill-focused dual task at all levels of practice.

The performance of concurrent cognitive tasks appears to reveal the focus of attention (Abernethy, 1988). Our results showed that performance of the two concurrent cognitive tasks changed gradually in opposite directions across training blocks. The decrease in the error rate in the extraneous dual task indicates that the amount of attention required for the keying sequence decreases with practice; execution of the keying sequence becomes more procedural, freeing the attentional resources needed to process an extraneous stimulus (Abernethy, 1988). On the other hand, the increased error rate in the skill-focused dual task shows that participants with higher levels of (primary) motor performance generally pay less attention to the information related to motor skill execution but are still prevented from entering motor chunk mode (Abernethy et al., 2007).

Limitations and Future Research

With respect to information processing, the RT data currently do not allow a separation between the sequence selection and sequence initiation stages (Dudman & Krakauer, 2016; Spijkers & Walter, 1985). Sequence selection would take place before sequence initiation and would provide a signal about what sequence is to be pressed. Sequence initiation would then load individual responses or motor chunks into the motor buffer and would take place prior to actual execution. In our study, both selection and initiation are contained within the RT, making it impossible to precisely distinguish which stage is affected. Differentiating separate components within RT should be further explored in future research.

Regarding the execution of the motor skill, the present design does not rule out alternative explanations that might also account for the discrepancy between our study and previous dual-task studies. First, the positive effects of the extraneous dual task might be due to the simplicity of the extraneous dual task used in the present study (Diekfuss et al., 2017). The performance of tone identification was generally better than key identification. And the IKIs at L_1 and L_2 in the skill-focused dual-task condition were slower than those in the extraneous dual-task condition in early blocks. Perhaps the extraneous dual task was not challenging enough to draw substantial attentional resources away from motor skill execution. Second, the comparably lower complexity of the motor skill could explain the apparent contradiction to previous findings. Gray (2004) found that the performance of novices in a simulated baseball-batting task was better in the skill-focused dual-task condition than the extraneous dual-task condition. We used the same dual-task methodology, while modified for the keying sequence, and also used the same extraneous dual task (identifying pitch of a tone). Still, compared to baseball batting, our keying sequence might be less complex and require less attention. This might have led to little cognitive-motor interference with motor skill execution in the extraneous dual-task condition (Gabbett & Abernethy, 2012). Third, it needs to be considered which skill level participants already had acquired after Phase 2? After familiarizing with the response board in Phase 1, participants in Phase 2 had to memorize two keying sequences within two blocks of 60 trials. Although an 800 ms RSI was used to prevent participants from practicing fast sequence execution, participants might more or less gain some proficiency in the motor skill (rather than only declarative knowledge). Perhaps, on motor skill execution, directing attention toward execution benefits individuals who are just novices or beginners without proficiency, whereas shifting attention away from execution benefits individuals who have attained perhaps even just a minimal proficiency (e.g., Beilock et al., 2002; 2004; Gray, 2004). Future investigations should thus vary the complexity of the extraneous dual task, the attentional demands of the motor tasks, and the amount of practice trials for memorizing keying sequences.

Furthermore, the results of the performance of concurrent cognitive tasks should be interpreted cautiously. The increase in error rate in the skill-focused dual task with practice might not only be due to the less attention paid to the execution. With the increasing speed of motor skill execution (the increasing speed of keying sequence), it might simply get more difficult to identify which key press was accompanied by a tone. With the current data, we cannot decide unambiguously whether this is the case. Additional experiments would be needed to elucidate this point.

Our results – at least with respect to MD – appear to align well with research on the effects of attentional focus instructions (Wulf, 2007, 2013). This line of research has generally found that an external focus on the intended movement effect (e.g., on an implement) results in better performance and faster learning as compared to an internal focus on body movements (Wulf, 2007, 2013). The distinction between internal and external, however, is somewhat orthogonal to our skill-focus vs. extraneous distinction. For example, in our study, participants were asked to monitor which keystroke was accompanied by a tone in the skill-focused dual-task condition. It is not clear whether the instruction led participants to attend to moving their fingers, which could be considered as an internal focus, or to the keys to be pressed, which could be considered as an external focus (Zentgraf et al., 2009). And the definition of extraneous focus is different from the definition of externally focused attention. The term extraneous focus refers to the focus on the extraneous stimulus not directly involved in the execution, whereas the external focus refers to the focus on the movement effect related to the execution (Castaneda & Gray, 2007). Attention to irrelevant auditory stimuli that are not involved directly in keying sequence execution is not an externally focused attention. Future research that hopes to link these two lines of research should operationalize skill-focused dual-task conditions in terms of an internal focus or external focus differently and give different attention conditions to movement effects and irrelevant environmental stimuli respectively.

Conclusion

In summary, our findings suggest that the effects of attentional direction depend not only on the amount of practice but also on the stage of information processing. Regarding the selection and initiation of motor skills, our results showed that the skill-focused dual-task condition is more advantageous during early practice. We argue that maintaining a requirement of paying attention to motor skill execution in the working memory might require less effort and demand less cognitive resources than maintaining a requirement of paying attention to an extraneous stimulus during the early practice. Future research should explore the impact of the direction of attention on different components within the premotor stages of information processing (i.e., motor skill selection and motor skill initiation), such as by examining increasing stimulus onset asynchrony. Moreover, regarding the execution of motor skills, our results suggest that there is no universal explanation that can fully explain the performance patterns across skill levels exhibited in dual-task conditions. The motor skill execution in dual-task conditions seems to be influenced by a variety of factors, such as the direction of attention manipulated by dual tasks (i.e., concurrent cognitive tasks), the cognitive involvement demands and the difficulty level of dual tasks, the amount of practice, and the complexity of the motor skill. Future investigations could consider using a more complex extraneous dual task or motor task that demands more attention or quantifying levels of expertise. Regarding the performance of concurrent cognitive tasks, our results were in line with previous dual-task research.

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REFERENCES

Abernethy, B. (1988). Dual-task methodology and motor skills research: some applications and methodological constraints. *Journal of Human Movement Studies*, *14*(3), 101–132.

Abernethy, B., Maxwell, J. P., Masters, R. S., van der Kamp, J., & Jackson, R. C. (2007). Attentional processes in skill learning and expert performance. *Handbook of sport psychology*, *3*, 245–263.

Al-Yahya, E., Dawes, H., Smith, L., Dennis, A., Howells, K., & Cockburn, J. (2011). Cognitive motor interference while walking: a systematic review and meta-analysis. *Neuroscience & Biobehavioral Reviews*, *35*(3), 715–728.

Anderson, J. R. (1982). Acquisition of cognitive skill. *Psychological review*, *89*(4), 369–406. https://doi.org/10.1037/0033-295X.89.4.369

Anderson, J. R. (1983). *The architecture of cognition*. Harvard University Press.

Anderson, J. R. (1993). *Rules of mind*. Erlbaum.

Beilock, S. L., Bertenthal, B. I., McCoy, A. M., & Carr, T. H. (2004). Haste does not always make waste: Expertise, direction of attention, and speed versus accuracy in performing sensorimotor skills. *Psychonomic Bulletin & Review*, *11*(2), 373–379.

Beilock, S. L., & Carr, T. H. (2001). On the fragility of skilled performance: What governs choking under pressure? *Journal of Experimental Psychology: General*, *130*(4), 701–725.

Beilock, S. L., Carr, T. H., MacMahon, C., & Starkes, J. L. (2002). When paying attention becomes counterproductive: impact of divided versus skill-focused attention on novice and experienced performance of sensorimotor skills. *Journal of Experimental Psychology: Applied*, *8*(1), 6–16.

Beilock, S. L., & Gray, R. (2012). From attentional control to attentional spillover: A skill-level investigation of attention, movement, and performance outcomes. *Human movement science*, *31*(6), 1473–1499.

Castaneda, B., & Gray, R. (2007). Effects of focus of attention on baseball batting performance in players of differing skill levels. *Journal of Sport and Exercise Psychology*, *29*(1), 60–77.

Cohen, J. (1988). *Statistical power analysis for the behavioral sciences*. Routledge Academic.

Diekfuss, J. A., Ward, P., & Raisbeck, L. D. (2017). Attention, workload, and performance: A dual-task simulated shooting study. *International Journal of Sport and Exercise Psychology*, *15*(4), 423–437.

Dudman, J. T., & Krakauer, J. W. (2016). The basal ganglia: from motor commands to the control of vigor. *Current opinion in neurobiology*, *37*, 158–166.

Fitts, P. M., & Posner, M. I. (1967). *Human performance*. Brooks/Cole.

Gabbett, T. J, Wake, M., & Abernethy, B. (2011). Use of dual-task methodology for skill assessment and development: Examples from rugby league. *Journal of Sports Sciences*, *29*(1), 7–18.

Gabbett, T. J., & Abernethy, B. (2012). Dual-task assessment of a sporting skill: influence of task complexity and relationship with competitive performances. *Journal of Sports Sciences*, *30*(16), 1735–1745.

Gabbett, T. J., & Abernethy, B. (2013). Expert–novice differences in the anticipatory skill of rugby league players. *Sport, Exercise, and Performance Psychology*, *2*(2), 138.

Gray, R. (2004). Attending to the execution of a complex sensorimotor skill: expertise differences, choking, and slumps. *Journal of Experimental Psychology: Applied*, *10*(1), 42–54.

Ille, A., Selin, I., Do, M.-C., & Thon, B. (2013). Attentional focus effects on sprint start performance as a function of skill level. *Journal of Sports Sciences*, *31*(15), 1705–1712.

Jackson, R. C., Ashford, K. J., & Norsworthy, G. (2006). Attentional focus, dispositional reinvestment, and skilled motor performance under pressure. *Journal of Sport and Exercise Psychology*, *28*(1), 49–68.

Keele, S. W., & Summers, J. J. (1976). The structure of motor programs. In G. E. Stelmach (Ed.), *Motor control: Issues and trends* (pp. 109–142). Academic Press.

Kimble, G. A., & Perlmuter, L. C. (1970). The problem of volition. *Psychological Review*, *77*, 361–384.

Koch, I., Poljac, E., Müller, H., & Kiesel, A. (2018). Cognitive structure, flexibility, and plasticity in human multitasking—An integrative review of dual-task and task-switching research. *Psychological bulletin*, *144*(6), 557–583.

Kunde, W., Koch, I., & Hoffmann, J. (2004). Anticipated action effects affect the selection, initiation, and execution of actions. *The Quarterly Journal of Experimental Psychology Section A*, *57*(1), 87–106.

Langer, E., & Imber, G. (1979). When practice makes imperfect: Debilitating effects of overlearning. *Journal of Personality and Social Psychology*, *37*, 2014–2024 https://doi.org/10.1037/0022-3514.37.11.2014

Leavitt, J. (1979). Cognitive demands of skating and stickhandling in ice hockey. Canadian Journal of Applied Sport Sciences. *Journal canadien des sciences appliquees au sport*, *4*(1), 46–55.

Lewis, B., & Linder, D. (1997). Thinking about choking? Attentional processes and paradoxical performance. *Personality and Social Psychology Bulletin*, *23*, 937–944.

Marchant, D. C., Clough, P. J., Crawshaw, M., & Levy, A. (2009). Novice motor skill performance and task experience is influenced by attentional focusing instructions and instruction preferences. *International Journal of Sport and Exercise Psychology*, *7*(4), 488–502.

Masters, R. S. W. (1992). Knowledge, knerves and knowhow—The role of explicit versus implicit knowledge in the breakdown of a complex motor skill under pressure. *British Journal of Psychology*, 83, 343–358. https://doi.org/10.1111/j.2044-8295.1992.tb02446.x

Masters, R. S. W., Polman, R. C. J., & Hammond, N. V. (1993). 'Reinvestment': A dimension of personality implicated in skill breakdown under pressure. *Personality and individual differences*, *14*(5), 655–666.

Masters, R. S. W., Poolton, J. M., Maxwell, J. P., & Raab, M. (2008). Implicit motor learning and complex decision making in time-constrained environments. *Journal of motor behavior*, *40*(1), 71–79.

Nicolson, R., & Fawcett, A. (1990). Automaticity: A new framework for dyslexia research? *Cognition*, *35*(2), 159–182.

Nissen, M. J., & Bullemer, P. (1987). Attentional requirements of learning: Evidence from performance measures. *Cognitive psychology*, *19*(1), 1–32.

Patel, P., Lamar, M., & Bhatt, T. (2014). Effect of type of cognitive task and walking speed on cognitive-motor interference during dual-task walking. *Neuroscience*, *260*, 140–148.

Plant, R. R., Hammond, N., & Turner, G. (2004). Self-validating presentation and response timing in cognitive paradigms: How and why? *Behavior Research Methods, Instruments, & Computers*, *36*(2), 291–303.

Proctor, R. W., & Dutta, A. (1995). *Skill acquisition and human performance*. Sage.

Rhodes, B. J., Bullock, D., Verwey, W. B., Averbeck, B. B., & Page, M. P. (2004). Learning and production of movement sequences: Behavioral, neurophysiological, and modeling perspectives. *Human movement science*, *23*(5), 699–746.

Schaefer, S. (2014). The ecological approach to cognitive-motor dual-tasking: findings on the effects of expertise and age. *Frontiers in Psychology*, *5*, 1167. https://doi.org/10.3389/fpsyg.2014.01167

Schaefer, S., & Scornaienchi, D. (2020). Table tennis experts outperform novices in a demanding cognitive-motor dual-task situation. *Journal of motor behavior*, *52*(2), 204–213.

Schneider, W., & Shiffrin, R. M. (1977). Controlled and automatic human information processing: I. Detection, search, and attention. *Psychological review*, *84*(1), 1–66.

Smith, M. D., & Chamberlin, C. J. (1992). Effect of adding cognitively demanding tasks on soccer skill performance. *Perceptual and Motor Skills*, *75*(3), 955–961.

Spijkers, W. A., & Walter, A. (1985). Response processing stages in choice reactions. *Acta Psychologica*, *58*, 191–204.

Stöcker, C., & Hoffmann, J. (2004). The ideomotor principle and motor sequence acquisition: Tone effects facilitate movement chunking. *Psychological Research*, *68*(2-3), 126–137.

Thompson, V. A. (2013). Why it matters: The implications of autonomous processes for dual process Theories-Commentary on Evans & Stanovich (2013)). Perspective Psychology Science, *8*(3), 253–256. https://doi.org/10.1177/1745691613483476

Vuillerme, N., & Nougier, V. (2004). Attentional demand for regulating postural sway: The effect of expertise in gymnastics. *Brain Research Bulletin*, *63*(2), 161–165.

Winer, B. J., Brown, D. R., & Michels, K. M. (1991). *Statistical principles in experimental design* (3rd ed.). McGraw-Hill.

Wulf, G. (2007). Attentional focus and motor learning: A review of 10 years of research. *E-journal Bewegung und Training*, *1*(2-3), 1–11.

Wulf, G. (2013). Attentional focus and motor learning: A review of 15 years. *International Review of Sport and Exercise Psychology*, *6*(1), 77–104. https://doi.org/10.1080/1750984X.2012.723728

Zentgraf, K., Lorey, B., Bischoff, M., Zimmermann, K., Stark, R., & Munzert, J. (2009). Neural correlates of attentional focusing during finger movements: A fMRI study. *Journal of motor behavior*, *41*(6), 535–541.

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4.2 Article 2

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Summary:

Building up on the results of the first article, the aim of the second article was to understand in-depth the effects of different attentional conditions on the preparation phase of motor skill across practice. The study intended to disentangle the effects of different attentional conditions on the selection and initiation stages of motor sequence. The experimental design in this study was nearly identical to the experimental paradigm in the first article with one exception. Different stimulus onset asynchronies (SOA; 0, 300, 900 ms) between sequence label cue and a starting signal were used to give varying amounts of preparation time. The reaction time (RT, defined as the time between the starting signal and the first keypress) was used as an indicator of the performance of the preparation stage of motor sequence. The differences in RT between dual-task conditions in different SOA conditions were compared. The results indicate that in the 0 ms SOA condition, RTs in the skill-focused dual-task condition were initially faster than RTs in the extraneous dual-task condition, and the gap between RTs under the two different dual-task conditions gradually decreased with practice and vanished in the final block, which replicated the results of RTs in the first article. Most importantly, there was no difference in RT between two dual-task conditions in the 300 ms and 900 ms SOA conditions, that is, the advantage RT in the skill-focused condition was eliminated by increasing preparation time. The results suggest that a faster RT induced by the skill-focused dual-task condition is purely due to the facilitation of the sequence selection, and not the sequence initiation that occurs after the presentation of the starting signal.

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The Effect of Attentional Direction on Sub-Stages of Preparing for Motor Skill Execution Across Practice

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Abstract

While several empirical studies using dual-task methodology have examined the effect of attentional direction on motor skill execution; few have studied the effect of attentional direction on just the preparation phase of motor practice. In this study, via a keying sequence paradigm, we explored processing stages of preparation for a motor skill and disentangled the effect of attentional direction on various stages across practice. First, participants learned two keying sequences (three versus six keys). Then, they practiced the keying sequences in response to corresponding sequence labels under two block-wise alternating dual-task conditions. To dissect the preparation phase into sequence selection and sequence initiation stages, participants received varying amounts of preparation time (0, 300, 900 ms) before a starting signal instructed them to begin sequence execution. In each trial, a tone was paired with one of the three or six keypresses, and participants indicated either the keypress with which the tone was presented (skill-focused dual task) or the tone's pitch (extraneous dual task) after the sequence execution. We found that attentional direction affected only the sequence selection stage, not the sequence initiation stage. During early practice, compared to drawing attention away from execution, directing attention toward execution led to faster sequence selection. This advantage decreased with practice and vanished during late blocks of trials.

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Moreover, for the execution phase, relative to directing attention toward execution, drawing attention away from execution led to better performance of keying sequence execution across practice. Thus, attentional direction alone does not fully explain the difference between performance patterns at different skill levels in the dual-task literature; rather, types of motor skills and dual task difficulty levels may also drive performance differences.

Keywords
motor skill, dual task, attentional direction, preparation phase

Introduction

According to several theories of motor skill learning (e.g., Anderson, 1982; Fitts & Posner, 1967), attentional requirements for motor skills change with practice and experience. In early learning phases, motor skill execution is supported by a set of unintegrated components of the motor skill that should be kept in working memory and consciously attended to step-by-step (Beilock et al., 2004; Gray, 2004). Gradually, with extended practice, motor skill components are mediated more and more by procedural memory, and the motor skill, therefore, can be executed more automatically with minimum attentional demands (Anderson, 1982; Fitts & Posner, 1967). Such a decrease in attentional demands for executing a motor skill, which is caused by practice, has led researchers to investigate how attentional direction affects motor skill performance across skill levels — either by shifting attention away from execution or by drawing attention toward it. Studies to date, however, have mostly examined attentional direction effects on performance outcomes and, to some extent, on the execution phase (e.g., Beilock et al., 2002, 2004; Gray, 2004; Jackson et al., 2006), while few studies have examined its effect on the preparation phase.

To study the role of attentional direction in motor skill performance, previous studies have used "dual-task methodology" (e.g., Beilock et al., 2002, 2004; Beilock & Gray, 2012; Gray, 2004; Jackson et al., 2006), which refers to experiments in which participants perform a primary task related to the motor skill and, simultaneously, a secondary unrelated task, generally cognitive in nature. Two categories of secondary tasks have been distinguished: (a) a skill-focused dual task that directs attention toward motor skill execution (e.g., reporting the side of the foot contacting the ball while soccer dribbling), and (b) an extraneous dual task that draws attention away from motor skill execution (e.g., identifying irrelevant auditory stimuli). Previous studies using dual-task methodology have revealed that the effect of attentional direction differs across levels of motor skills (e.g., Beilock et al., 2002; 2004; Beilock & Gray, 2012; Castaneda & Gray, 2007; Gray, 2004; Jackson et al., 2006). An extraneous dual task hardly impacted high-skilled performance, but it greatly interfered with low-skilled performance (Beilock et al., 2002, 2004; Jackson et al., 2006). Skill-focused dual tasks, however, impaired high-skilled participants' performance to a greater degree than that of low-skilled participants (Beilock et al., 2002; Gray, 2004). In other words, low-skilled participants benefit more than high-skilled participants from directing attention toward, rather than away, from motor skill execution; whereas high-skilled participants show the opposite pattern.

For example, Gray (2004) asked participants to complete a motor task of simulated baseball batting under dual-task conditions. During each trial, one of two different tones (250 or 500 Hz) occurred during the swing phase of baseball batting. In the skill-focused dual-task condition, participants were required to verbally indicate whether the tone occurred during the downward or the upward phase of the swing at the instant the tone was presented; in the extraneous dual task, participants were required to indicate whether the tone was the higher or the lower pitched tone at the instant the tone was presented. Novices' batting performance was better in the skill-focused dual-task condition than in the extraneous dual-task condition, but experts displayed superior batting performance in the extraneous dual-task condition relative to the skill-focused dual-task condition. Similar results have been reported for a golf putting task (Beilock et al., 2002; Beilock & Gray, 2012) and a soccer dribbling task (Beilock et al., 2002; Jackson et al., 2006).

Low-skilled participants are expected to attend to motor skill execution without specific direction to do so, since conscious processing is used to control execution in a step-by-step fashion. Hence, directing attention toward motor skill execution should not be disruptive to their performance. In contrast, when engaging in an extraneous dual task in addition to their primary task, low-skilled participants' performance is impaired due to insufficient availability of attentional resources. However, for high-skilled participants, the motor skill can be executed automatically without attentional monitoring. Drawing attention away from motor skill execution should not impair their performance, because they can direct most of their attentional resources to process the extraneous dual task. In contrast, directing attention toward motor skill execution would hinder their performance by bringing elements of motor skill back into working memory, resulting in a breakdown of automatic mechanisms (Castaneda & Gray, 2007; Ford et al., 2005).

Most previous studies using dual-task methodology have examined these attentional direction effects on motor skill execution and performance outcomes, leaving still unclear how attentional direction affects the preparation phase of motor skill execution. In the motor skill preparation phase, the individual must select appropriate motor schemas according to proper internal and external cues and then must organize these schemas into a suitable sequence (Jeannerod, 1997). Both motor skill preparation and execution phases are critically important for any motor task that requires rapid responses to signals and a coordination of multiple effectors (Ille et al., 2013). However, most primary motor tasks in dual-task research have been continuous or self-paced tasks that participants began executing when they were ready and that did not require a short reaction time.

A recent study (Luan et al., 2020) proposed an advantage for drawing attention toward motor skill execution for the preparation phase in early practice but suggested that this advantage diminished with practice. Luan et al. (2020) had participants learn two keying sequences (a three-key and a six-key sequence, labeled X and Y respectively) and then practice them in response to the label cue (X or Y) under two different dual-task conditions. During each keying sequence execution, a tone was presented along with one of the keypresses. In the extraneous dual-task condition, participants finished the keying sequence execution and then indicated whether the tone was of a higher or lower pitch. In the skill-focused dual-task condition, they completed the keying sequence and then indicated the keypress with the tone presentation. Reaction times (defined as the time between the presentation of the sequence label cue and the first keypress) were faster in the skill-focused dual-task condition than in the extraneous dual-task condition, and the gap between reaction times in the two dual-task conditions decreased and diminished with practice.

Although Luan et al. (2020) results clearly showed how attentional direction influences the preparation phase of a keying sequence across practice, these results did not differentiate attention direction effects on sub-stages of the preparation phase. In a traditional information-processing stage theory of keying sequences, both sequence selection and sequence initiation can be treated as separate serial sub-stages of a cognitive process encapsulated within the preparation phase (Dudman & Krakauer, 2016; Kunde et al., 2004; Spijkers & Walter, 1985; Stöcker & Hoffmann, 2004). Sequence selection precedes sequence initiation and provides the signal for executing the keying sequence, corresponding with the stimulus. Sequence initiation initiates the selected keying sequence and occurs before the execution phase. Luan et al. (2020) included both selection and initiation stages within the reaction time measure, meaning that this study could not distinguish which sub-stage was influenced by attentional direction.

Therefore, in the present study, our main purpose was to better understand how attentional direction influences the preparation phase of motor skill execution across practice. We intended to disentangle attentional direction's influence on selection and initiation stages of keying sequence. This study's experimental design was nearly identical to Luan et al. (2020) paradigm, with one exception. We used different stimulus onset asynchronies (SOAs; 0, 300, 900 ms) between the presentation of the sequence label cue and the starting signal in order to provide participants with varying amounts of preparation time. We used the participants' reaction time (RT), defined as the time between the starting signal and the first keypress and differing from that in Luan et al.

(2020), to indicate performance of the separate sub-stages of the preparation phase of the keying sequence. We compared the difference in RT between dual-task conditions in different SOA conditions. The rationale for manipulating SOA was that if increasing SOA between the presentation of the sequence label cue and the starting signal has no differential influence on RT differences between dual-task conditions, then attentional direction differentially affects the sequence initiation stage, not the sequence selection stage. If increasing SOA decreases RT differences between dual-task conditions, then attentional direction affects sequence selection and/or sequence initiation stages. If sufficiently long SOAs result in no difference in RTs between dual-task conditions, then attentional direction affects only the sequence selection stage, not the sequence initiation stage. We also used movement duration (MD), also known as "movement time," (the same as in Luan et al., 2020) to indicate the performance of the execution phase of the keying sequence, since we also wanted to explore whether different SOA conditions affected performance in the execution stage.

Method

Participants

Thirty-two undergraduate and graduate students (15 male, 17 female) with an age range between 19 and 28 years ($M = 23.2$, $SD = 2.1$) participated in this study for extra credit. All participants were right-handed and naive to dual-task methodology and to the keying sequence task. Invited to the lab individually, they first received a short tour. They were then informed about the experimental procedure, their rights, and the anonymity of experimental data. Finally, they were asked to sign an informed consent form, according to Declaration of Helsinki guidelines. For reasons explained below, one participant's data was excluded from analysis. The study did not involve any invasive or potentially dangerous methods. According to the German Science Foundation and the guidelines of the first author's institution, formal ethical approval was not required.

Apparatus

Presentation of stimuli and registration of responses were achieved by MATLAB 2017 b (the MathWorks Inc., Natick, MA, USA) and the Psychtoolbox-3 extensions (http://psychtoolbox.org/) on a PC (FUJITSU DTF, Intel (R) Core (TM) i7-7700, 3.60 GHz CPU, 16 GB RAM, 64-bit Windows 10). Stimuli were presented on a 17-inch Dell E1715S monitor, approximately 50 cm in front of participants. The screen's spatial resolution was set to 1024 × 768. In the experiment, the screen's background was black, and the instructions were in white 16-point Arial font. Tones were presented via two loudspeakers located approximately 20 cm bilaterally from the monitor.

The experiment employed one custom-built keyboard, consisting of two "BLACK BOX TOOLKIT" four-button response pads. Eight keys of the two response pads were relocated as a horizontal line across the keyboard's vertical center and labeled with eight letters (A, S, D, F, G, H, J, and K). Throughout the experiment, participants rested their left index, middle, ring, and little fingers on buttons corresponding to F, D, S, and A keys, respectively, and rested their right index, middle, ring, and little fingers on buttons corresponding to G, H, J, and K keys, respectively.

Study Design and Procedure

The primary task in the present study was to learn two bimanual keying sequences and practice them in two dual-task conditions (skill-focused and extraneous) — a modified design from that of Luan and colleagues (2020). The experiment consisted of three phases (the familiarization phase, the acquisition phase, and the test phase). At the beginning of each phase, we presented instructions as text on the screen. Figure 1 presented the flow chart of the procedure. Figure 2 displayed the trial types in the acquisition phase and the test phase.

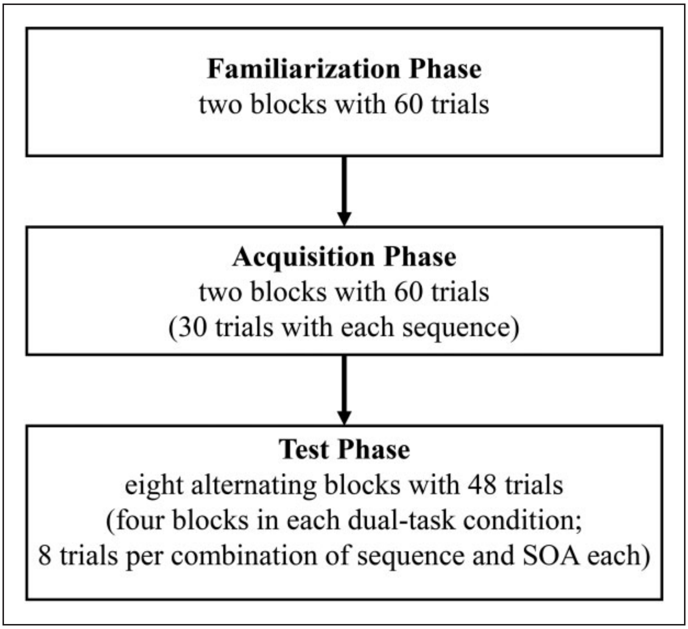

Figure 1. Flow Chart of the Procedure.

Familiarization Phase

Participants learned about the apparatus and stimuli during the familiarization phase, which consisted of two blocks with 60 trials each. In each trial, participants were presented one of the six letters (S, D, F, G, H, or J) in white 16-point Arial font at the monitor's center, and they were to press the assigned key as quickly as possible. Letters were presented randomly, each occurring equally often. When a participant pressed the correct key, after an 800-ms interval, the next trial presented the next letter stimulus. When a participant pressed a wrong key, the message "Error" appeared for 700 ms at the bottom of the screen. Then, after an 800-ms interval, the next trial began.

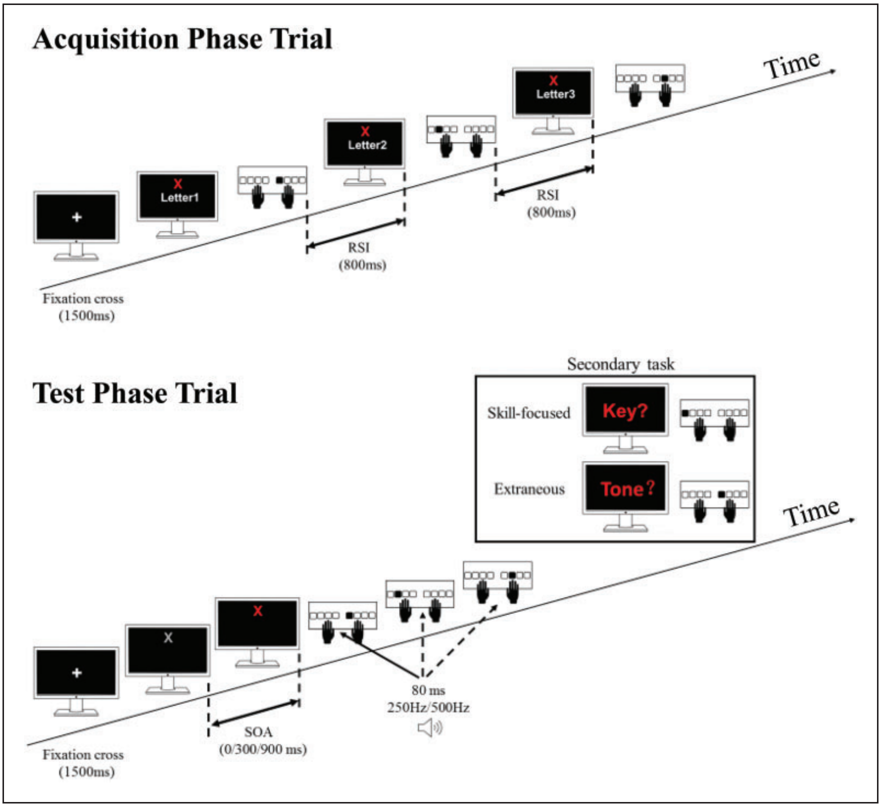

Figure 2. Schematic Illustration of the Display and the Timing of Events in the Acquisition Phase and the Test Phase. Note: We used the three-key sequence labeled X trials as examples. They could also be the six-key sequence labeled Y trials.

Acquisition Phase: Learning Keying Sequences

In the second phase, participants learned two keying sequences in response to single sequence-specific letters, a short one labeled “X” and a long one labeled “Y.” With the letters “R,” “M,” and “I” standing for ring, middle, and index fingers and lowercase standing for the left hand, for all participants, the short sequence was I-r-M (learned as G-S-H) and the long sequence was r-I-i-M-m-R (learned as S-G-F-H-D-J).

In this phase, the term “trial” indicated an entire sequence. In each trial, after presentation of a white fixation cross (approximately 0.70° of visual angle) for 1,500 ms, a sequence label (“X” or “Y”) in white 60-point Arial font appeared throughout the entire trial in the monitor’s upper half. Then the first letter of the sequence with that label was presented at the center point, and participants pressed the corresponding key, as in the familiarization phase. When the participant pressed the correct key, the next letter of that sequence appeared after a response-to-stimulus interval (RSI; the delay between a participant’s response and the next stimulus’s appearance) of 800 ms. RSI manipulation prevented participants from practicing fast execution of keying sequences in this phase but enabled them to build up central-symbolic representations of the two sequences (Luan et al., 2020). If a wrong key was pressed, the message “Error” appeared for 700 ms at the bottom of the monitor before the RSI. After the entire sequence ended, the sequence label cue disappeared, and the next trial began. Participants were instructed to focus on memorizing the two sequences and minimizing mistakes, not necessarily to react fast because they would later be asked to execute keying sequences based on the stimulus of the sequence label alone without a key-specific cue. This phase contained two blocks each consisting of 60 trials (30 trials with each sequence). Sequence order was randomized across each block. After each block, participants’ error rate for that block appeared on the monitor for five seconds.

Test Phase: Performing in Dual-Task Conditions

The test phase consisted of eight alternating blocks, each with one of the dual-task conditions (skill-focused or extraneous); the starting condition was counterbalanced across participants. Each block began with an instruction on the screen about the block’s dual-task version. In each test phase trial, a fixation cross appeared at the monitor’s center for 1500 ms, after which the sequence-specific cue (“X” or “Y”) appeared. The three different SOA conditions were 0 ms, 300 ms, and 900 ms. In trials with an SOA different from 0 ms, the sequence cue was first presented in white. After the SOA had passed, the color of the sequence cue changed to red. In trials with 0 ms SOA, the sequence cue letter was presented in red directly. Participants were supposed to initiate immediately and execute the corresponding keying sequence as quickly as possible without mistakes after the SOA passed (i.e., the cue color changed to red). Note that in this phase, key-specific cues did not appear. Either one 80-ms low-pitched tone (250 Hz) or one 80-ms high-pitched tone (500 Hz) was presented to participants with the pressing of one of the three or six keys in each trial. The keystroke with which the tone was paired and the tone's frequency were randomly, but equally, distributed. At the beginning of the test phase, for familiarization, the two tones were presented five times in alternation.

In the skill-focused dual-task condition, participants monitored which keypress was accompanied by the tone. After completing each sequence, they reported the keystroke by pressing the corresponding key (S, D, F, G, H, or J). In the extraneous dual-task condition, participants carefully monitored the tone's frequency. After completing each sequence, they identified whether the tone was low-pitched or high-pitched by pressing a corresponding key ("A" for low frequency and "K" for high frequency). After participants answered the question about the concurrent cognitive task, the next trial started automatically. When a wrong key was pressed during the keying sequence execution, the word "Error" appeared (red 16-point Arial) for 700 ms at the bottom of the screen. Then, the current trial was aborted, and the next trial began.

Each block consisted of 48 trials (24 with each sequence). The combination of sequence and SOA varied randomly, but occurred equally, often in each block; that is, there were eight trials per combination of sequence and SOA. At the end of each block, the error rate and the mean RT of the keying sequence task for that block appeared onscreen for five seconds. Each block was followed by a 30-second break except for block 4 (60 seconds).

Data Processing and Statistical Analysis

Only test phase trials were analyzed. One male participant was not included in the analysis due to failure to remember the two sequences and therefore an inability to complete the test phase. Each participant's RT and MD were recorded for each trial. RT was measured as the time from the moment the sequence cue turned red to the first keypress; MD was measured as the time from the first to the last keypress. To reduce the influence of transitioning from one dual-task condition to another (i.e., sequentially), each block's first two trials were excluded from analysis. Furthermore, trials containing a wrong keypress were considered erroneous and excluded. In the end, for each participant, more than 95% of "X" sequence trials and 90% of "Y" sequence trials remained. We analyzed mean RT and MD per participant, sequence, dual-task condition, SOA, and block by using a 2 (Sequence: 3-key vs. 6-key) × 2 (Dual-task: skill-focused vs. extraneous) × 3 (SOA: 0 ms, 300 ms, 900 ms) × 4 (Block) analyses of variance (ANOVAs) with repeated measurement. Where significant Dual-task × SOA × Block interaction occurred, separate ANOVAs with Sequence, Dual-task, and Block as factors for each SOA condition were conducted to examine Dual-task × Block interaction in different SOA conditions. We applied the Greenhouse–Geisser correction when Mauchly's test indicated that the assumption of sphericity was violated. Estimated marginal means and differences between estimated marginal means were calculated to represent main effects and interaction effects.

Results

Reaction Time

The ANOVA revealed a main effect of Block, $F(1.16, 34.86) = 43.72$, $p < 0.001$, $\eta_p^2 = 0.59$, indicating that RTs decreased with practice. There was a main effect of Sequence, $F(1, 30) = 12.75$, $p = 0.001$, $\eta_p^2 = 0.30$, showing that RTs in the three-key sequence were shorter than RTs in the six-key sequence. There was also a main effect of SOA, $F(1.50, 45.11) = 253.85$, $p < 0.001$, $\eta_p^2 = 0.89$, such that RTs decreased with increasing SOA (0 ms SOA: $M = 883$ ms; 300 ms SOA: $M = 628$ ms; 900 ms SOA: $M = 409$ ms). A significant SOA × Block interaction, $F(2.80, 83.94) = 6.21$, $p = 0.001$, $\eta_p^2 = 0.17$, indicated that SOA effect on RT decreased with practice. Statistical significance was observed in the main effect of Dual-task, showing faster RT in the skill-focused dual-task condition ($M = 615$ ms) than in the extraneous dual-task condition ($M = 664$ ms), $F(1, 30) = 4.22$, $p = 0.049$, $\eta_p^2 = 0.12$. The main effect of Dual-task was qualified by a significant Dual-task × SOA interaction, $F(1.79, 53.76) = 7.41$, $p = 0.002$, $\eta_p^2 = 0.20$, showing that RT difference between the two dual-task conditions decreased with increased SOA (differences between estimated marginal means for dual-task conditions across SOA conditions were 97, 35, and 23 ms for 0-ms, 300-ms, and 900-ms SOA conditions, respectively). In addition, a significant Dual-task × SOA × Block interaction, $F(2.65, 79.56) = 3.2$, $p = 0.033$, $\eta_p^2 = 0.10$, suggested that RT difference between the two dual-task conditions in early practice blocks decreased more with increased SOA. All other interactions were nonsignificant, $p\text{s} > 0.19$ (Figure 3).

To investigate this three-way interaction further, we conducted three separate ANOVAs for the three SOA conditions with Sequence, Dual-task, and Block as factors. In the 0-ms SOA condition, a significant main effect of Dual-task was observed, $F(1, 30) = 11.75$, $p = 0.002$, $\eta_p^2 = 0.28$, showing faster RT in the skill-focused dual-task condition ($M = 834$ ms) than in the extraneous dual-task condition ($M = 931$ ms). The Dual-task × Block interaction was also significant, $F(1.50, 45.05) = 3.74$, $p = 0.043$, $\eta_p^2 = 0.11$, such that RT difference between the two dual-task conditions decreased with practice (differences between estimated marginal means for dual-task conditions across practice were 253, 76, 44, and 7 ms for Blocks 1–4, respectively). Further planned comparisons detected that RT in the skill-focused dual-task condition was faster than the extraneous dual-task condition in the first two blocks, $F\text{s}(1, 30) < 6.49$, $ps > 0.016$, $\eta_p^2\text{s} > 0.18$,

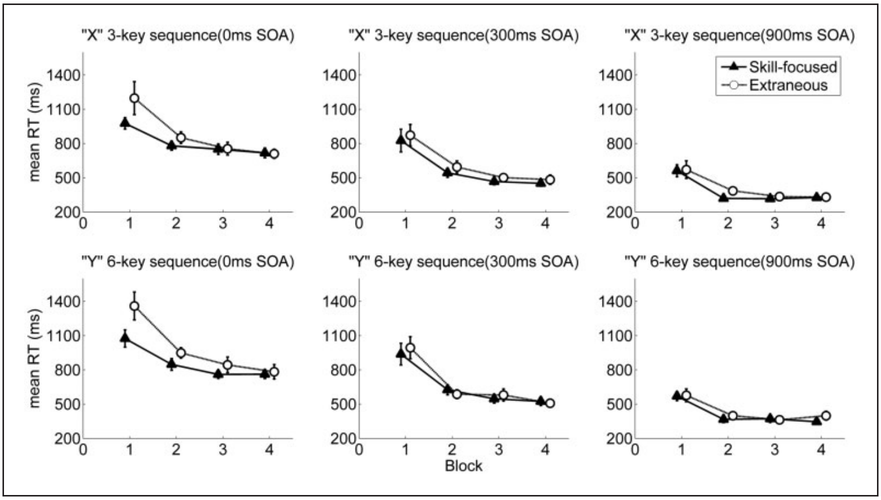

Figure 3. Reaction Time as a Function of Block, Dual Task, SOA, and Sequence. Note: Error bars represent standard errors.

whereas no RT differences were found for Blocks 3 and 4, $Fs(1, 30) < 1.09$, $ps > 0.30$. However, in the other two SOA conditions (300 ms and 900 ms), ANOVAs showed that neither the main effect dual-task nor the dual-task × -block interaction approached significance, $ps > 0.24$.

Movement Duration

The ANOVA showed a significant main effect of Sequence, $F(1, 30) = 90.86$, $p < 0.001$, $\eta_p^2 = 0.75$, and a significant main effect of Block, $F(1.08, 32.46) = 65.34$, $p < 0.001$, $\eta_p^2 = 0.69$, indicating that MD decreased with practice and that it was shorter in the three-key than in the six-key sequence. A significant Sequence × Block interaction, $F(1.15, 34.38) = 30.97$, $p < 0.001$, $\eta_p^2 = 0.51$, indicated that the difference in MD between the two sequences decreased with practice (differences between estimated marginal means for sequences across practice were 1530, 982, 880, and 781 ms for Block 1–4, respectively). There was also a significant main effect of Dual-task, $F(1, 30) = 7.08$, $p < 0.012$, $\eta_p^2 = 0.19$, indicating that MD was generally slower in the skill-focused dual-task condition ($M = 1032$ ms) than in the extraneous dual-task condition ($M = 911$ ms). Moreover, a significant Dual-task × Sequence interaction, $F(1, 30) = 4.19$, $p = 0.049$, $\eta_p^2 = 0.12$, suggested that the MD difference between the two dual-task conditions was larger in the six-key than in the three-key sequence. The main effect of SOA was not statistically significant, and neither were other interactions, $ps > 0.12$ (Figure 4).

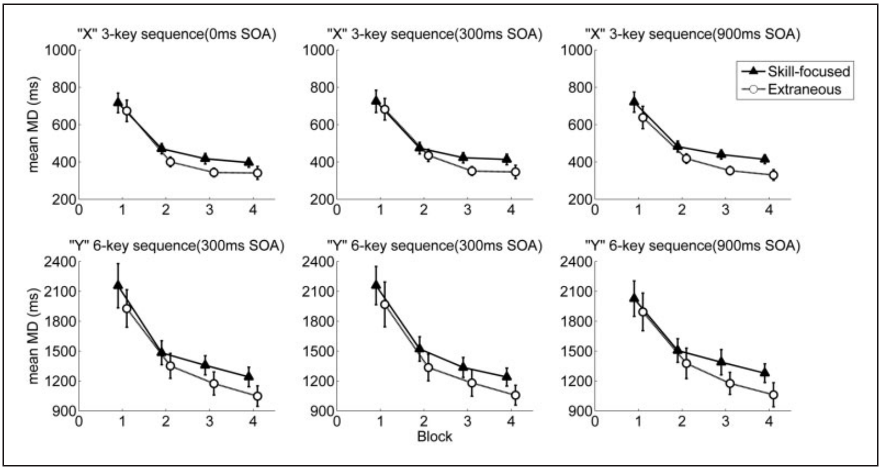

Figure 4. Movement Duration as a Function of Block, Dual Task, SOA, and Sequence. Note: Error bars represent standard errors.

Discussion

The present study examined the effect of attentional direction on sub-stages of the preparation phase of a motor skill — consisting of selection and initiation — for keying a sequence under a dual-task paradigm across practice. Our results indicated that in the 0-ms SOA condition, RTs in the skill-focused dual-task condition were initially faster than RTs in the extraneous dual-task condition, and the gap between RTs under the two different conditions gradually decreased with practice and vanished in the final block. This part of our results replicated previous findings by Luan et al. (2020). Most importantly, there was no difference in RT between the two dual-task conditions in the 300-ms and 900-ms SOA conditions, that is, the RT advantage in the skill-focused condition was eliminated by increasing preparation time. In addition, we analyzed the effect of attentional direction on the execution phase of keying sequences in different SOA conditions. We found that for MD, SOA conditions had no differential influence on the effect of attentional direction. Furthermore, results showed that directing attention toward execution generally impaired execution more than shifting attention away from execution, thus also replicating MD results in Luan et al. (2020).

Results for the preparation phase of the keying sequence showed that during early practice, the skill-focused dual-task condition was more beneficial than the extraneous dual-task condition when the SOA was set to 0 ms. These results indicated that directing attention toward, rather than away from, execution benefited the preparation phase of keying sequences; however, with increased SOA (from 0 to 300 and 900 ms), there were no differences in RT performance between dual-task conditions across practice. This indicates that the disadvantageous influence of shifting attention away from execution during early practice can be counteracted with additional preparation time. In turn, this strongly suggests that faster RT induced by the skill-focused dual-task condition is due to facilitation of sequence selection, not sequence initiation that occurs after presentation of the starting signal (Kunde et al., 2004; Stöcker & Hoffmann, 2004).

These results suggest that, during early practice, participants selected the keying sequence to respond to a sequence label cue by searching and retrieving explicit knowledge of the keying sequence (this sequence's series of letters) from memory (Anderson, 1982; Beilock & Gray, 2012; Fitts & Posner, 1967). Search and retrieval processes required working memory engagement (Thompson, 2013). Meanwhile, participants had to maintain the secondary task requirement in working memory (Koch et al., 2018). The skill-focused dual-task required them to pay attention to execution, and the extraneous dual-task required them to shift attention away from execution and pay attention to an extraneous stimulus (Luan et al., 2020). Clearly, novices were inclined to focus their attention on the motor skill itself and dismiss irrelevant information while preparing their motor skill execution (Anderson, 1982; Fitts & Posner, 1967). Therefore, during early practice, maintaining an attentional focus on an extraneous stimulus might require their greater effort and entail higher working memory engagement than maintaining attention to keying sequence execution, because the latter fits their attention's natural direction (Marchant et al., 2009). Consequently, when the SOA was set to 0 ms, the sequence selection sub-stage of the preparation phase of the keying sequence was slower in the extraneous dual-task condition because more cognitive resources were needed for maintaining the requirement of extraneous dual task and fewer cognitive resources were available for motor skill preparation. Across time, with sufficient practice, explicit knowledge of keying sequences became part of a mental representation of the sequence label cue (Luan et al., 2020; Thompson, 2013). In this circumstance, the keying sequence could be selected without the need for as many cognitive resources. Thus, the sequence selection would not be affected by the dual-task conditions. As a result, differences in RTs caused by dual-task conditions in trials with 0-ms SOA disappeared with practice.

Regarding the execution phase of the keying sequence, the analysis of MD indicated that keying sequence execution in the skill-focused dual-task condition was generally slower compared to the extraneous dual-task condition, independent of practice and preparation time. This result aligns with MD results in Luan et al. (2020). However, this result is inconsistent with typical low-skilled performance in the dual-task literature. Inexperienced performers have typically displayed superior performance in the skill-focused dual-task condition relative to the extraneous dual-task condition (e.g., Beilock et al., 2002; 2004; Gray, 2004). Two, not mutually exclusive, explanations may explain these contradictory results. First, given that the keying sequence is itself a high-speed motor task, deciding with which keypress a tone has been paired during such a fast keying sequence execution is difficult and requires significant attention, even during early practice. At the beginning of practice, participants attend to components of motor skill execution (Masters, 1992, 1993) and use a consciously controlled approach to execute keying sequences (Anderson, 1982; Fitts & Posner, 1967). Although controlled attentional processes take time to execute (Posner & Snyder, 1975), the speed of keying sequence execution is still too fast for assessing the keypress according to tone in the skill-focused dual-task condition. Therefore, to assess the keypress correctly, participants might actively slow keying sequence execution. Additionally, because the skill-focused dual-task requires large amounts of attention, attentional resources should be partly occupied by the skill-focused dual-task, leading to fewer available resources for keying sequence execution and, hence, a relatively slow keying sequence execution in the skill-focused dual-task condition (Luan et al., 2020).

Another explanation might be the extraneous dual task's simplicity. From a skill acquisition and automaticity standpoint, extraneous dual-task impairment in novice performance results from insufficient available attentional resources to support concurrent motor skill execution and dual-task performance (Beilock et al., 2004). This study's extraneous dual task presented only two possible tones. Arguably, such a simple design does not demand such substantial attentional resources as to prevent novices from attending to execution and to interfere with their motor skill execution (Gabbett & Abernethy, 2012). Thus, in our study, participants could execute the keying sequence without interruption by the extraneous dual task even at the beginning of practice.

Our MD results revealed the possibility that skill-focused dual task can cause interference with motor skill execution, leading to degraded performance during early practice. Both explanations emphasize that attentional direction manipulated by dual tasks alone does not fully explain the difference between performance patterns at different skill levels seen in the dual-task literature; rather, types of motor skill and difficulty levels of dual tasks could also drive performance differences (Raisbeck & Diekfuss, 2015).

Limitations and Directions for Future Research

The scope of this study was limited in terms of participants' proficiency, as it is not clear which level of skill they reached after the acquisition phase. Although we set an 800-ms RSI to prevent participants from quickly executing the keying sequence, participants might still have gained some proficiency in this motor skill (Luan et al., 2020). Perhaps, for the execution phase, only novices or beginners without proficiency profit from directing attention toward execution (e.g., Beilock et al., 2004; Gray, 2004). Future investigations should thus find a way to quantify levels of expertise across practice.

Another limitation of this study was the simplicity of the extraneous dual task. It is possible that the extraneous dual task used in this study was not challenging enough to lead a cognitive-motor interference with keying sequence execution (Gabbett & Abernethy, 2012). Future research might consider using sufficiently more difficult extraneous dual tasks to see whether the performance patterns at different skill levels were influenced. Using different extraneous dual tasks with different attentional resources demand would aid in the understanding of the role of difficulty levels of dual tasks in motor skill execution in dual-task conditions.

A further aspect, possibly limiting the extent to which conclusions might be generalized to other conditions or motor skills, was our somewhat reductionist approach. First, we took a serial-processing stand, assuming that the mental process can be divided into strictly independent sequential stages (e.g., Sanders, 1980). Secondly, we investigated a fairly simple ballistic, discrete motor skill. Modern models of decision making, however, indicate not only parallel processing (e.g., action selection and initiation, where different "stages" might interact; Hommel et al., 2001), but also allow for "early" processes to continue and for action selection information processing to be active until the very end of an action (Wispinski et al., 2018). Future research using different paradigms (e.g., reaching or point tasks) is needed in order to explore the effect of attentional direction on such interactions and continued processing.

Investigations of the neural mechanisms underlying sequence learning and execution are also strongly recommended. This type of research would benefit from employing brain imaging techniques, such as functional Magnetic Resonance Imaging (fMRI), magnetoencephalography (MEG), and electroencephalography (EEG) to shed light on brain activity during motor skill learning and performance in dual-task conditions. For example, EEG studies have already shown that the power of neural oscillation in the range of high-alpha in the left temporal region (e.g., Kerick et al., 2004) and the co-activation (coherence) between the left temporal region and the frontal midline region at the high-alpha frequency bandwidth (e.g., Deeny et al., 2003; Zhu et al., 2011) reflect the conscious involvement and attentional demands during motor skill learning and performance (Bellomo et al., 2018; Zhu et al., 2011). Because the dual-task methodology manipulates the direction of attention and influences the conscious involvement in motor skill learning and performance (Beilock & Gray, 2012), these measures of brain activity could also be sensitive to dual-task conditions.

Conclusion

In sum, the current study showed the effect of varying attentional direction on the different processing in sub-stages of the motor skill preparation phase across practice, using a keying sequence paradigm. Our results suggest that both the amount of practice and the sub-stages of the preparation phase can influence the effect of attentional direction. Moreover, we demonstrated that for the execution phase, attentional direction alone does not fully explain the general performance pattern seen in the dual-task literature; rather, types of motor skills and difficulty levels of dual tasks could also drive performance differences. To dissect different processing stages of a motor skill is a new perspective in dual-task research. This study furthered our knowledge of the effects of dual-task attentional manipulations, and this knowledge will help enhance performance at different stages of information processing. Future research that incorporates not only complex human motor skills with high ecological validity but also information on preparation phase brain activity will provide a more complete picture.

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Declaration of Conflicting Interests

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References

Anderson, J. R. (1982). Acquisition of cognitive skill. *Psychological Review*, *89*(4), 369–406.

Beilock, S. L., Bertenthal, B. I., McCoy, A. M., & Carr, T. H. (2004). Haste does not always make waste: Expertise, direction of attention, and speed versus accuracy in performing sensorimotor skills. *Psychonomic Bulletin & Review*, *11*(2), 373–379.

Beilock, S. L., Carr, T. H., MacMahon, C., & Starkes, J. L. (2002). When paying attention becomes counterproductive: Impact of divided versus skill-focused attention on novice and experienced performance of sensorimotor skills. *Journal of Experimental Psychology: Applied*, *8*(1), 6–16.

Beilock, S. L., & Gray, R. (2012). From attentional control to attentional spillover: A skill-level investigation of attention, movement, and performance outcomes. *Human Movement Science*, *31*(6), 1473–1499.

Bellomo, E., Cooke, A., & Hardy, J. (2018). Chunking, conscious processing, and EEG during sequence acquisition and performance pressure: A comprehensive test of reinvestment theory. *Journal of Sport & Exercise Psychology*, *40*(3), 135–145.

Castaneda, B., & Gray, R. (2007). Effects of focus of attention on baseball batting performance in players of differing skill levels. *Journal of Sport & Exercise Psychology*, *29*(1), 60–77.

Deeny, S. P., Hillman, C. H., Janelle, C. M., & Hatfield, B. D. (2003). Cortico-cortical communication and superior performance in skilled marksmen: An EEG coherence analysis. *Journal of Sport and Exercise Psychology*, *25*(2), 188–204.

Dudman, J. T., & Krakauer, J. W. (2016). The basal ganglia: From motor commands to the control of vigor. *Current Opinion in Neurobiology*, *37*, 158–166.

Fitts, P. M., & Posner, M. I. (1967). *Human performance*. Brooks/Cole.

Ford, P., Hodges, N. J., & Williams, A. M. (2005). Online attentional-focus manipulations in a soccer-dribbling task: Implications for the proceduralization of motor skills. *Journal of Motor Behavior*, *37*(5), 386–394.

Gabbett, T. J., & Abernethy, B. (2012). Dual-task assessment of a sporting skill: Influence of task complexity and relationship with competitive performances. *Journal of Sports Sciences*, *30*(16), 1735–1745.

Gray, R. (2004). Attending to the execution of a complex sensorimotor skill: Expertise differences, choking, and slumps. *Journal of Experimental Psychology: Applied*, *10*(1), 42–54.

Hommel, B., Müsseler, J., Aschersleben, G., & Prinz, W. (2001). The theory of event coding: A framework for perception and action planning. *Behavioral and Brain Sciences*, *24*(5), 849–937.

Ille, A., Selin, I., Do, M.-C., & Thon, B. (2013). Attentional focus effects on sprint start performance as a function of skill level. *Journal of Sports Sciences*, *31*(15), 1705–1712.

Jackson, R. C., Ashford, K. J., & Norsworthy, G. (2006). Attentional focus, dispositional reinvestment, and skilled motor performance under pressure. *Journal of Sport and Exercise Psychology*, *28*(1), 49–68.

Jeannerod, M. (1997). *The cognitive neuroscience of action*. Blackwell.

Kerick, S. E., Douglass, L. W., & Hatfield, B. D. (2004). Cerebral cortical adaptations associated with visuomotor practice. *Medicine and Science in Sports and Exercise*, *36*(1), 118–129.

Kunde, W., Koch, I., & Hoffmann, J. (2004). Anticipated action effects affect the selection, initiation, and execution of actions. *The Quarterly Journal of Experimental Psychology Section A*, *57*(1), 87–106.

Luan, M., Mirifar, A., Beckmann, J., & Ehrlenspiel, F. (2020). The varying effects of dual tasks on the performance of motor skills across practice. *Journal of Motor Behavior*. Advance online publication.

Marchant, D. C., Clough, P. J., Crawshaw, M., & Levy, A. (2009). Novice motor skill performance and task experience is influenced by attentional focusing instructions and instruction preferences. *International Journal of Sport and Exercise Psychology*, *7*(4), 488–502.

Masters, R. S. W. (1992). Knowledge, knerves and know-how—The role of explicit versus implicit knowledge in the breakdown of a complex motor skill under pressure. *British Journal of Psychology*, *83*(3), 343–358.

Masters, R. S. W., Polman, R. C. J., & Hammond, N. V. (1993). 'Reinvestment': A dimension of personality implicated in skill breakdown under pressure. *Personality and Individual Differences*, *14*(5), 655–666.

Posner, M. I., & Snyder, C. R. R. (1975). Attention and cognitive control. In R. L. Solso (Ed.), *Information processing and cognition: The Loyola symposium* (pp. 55–85). Wiley.

Raisbeck, L. D., & Diekfuss, J. A. (2015). Fine and gross motor skills: The effects on skill-focused dual-tasks. *Human Movement Science*, *43*, 146–154.

Sanders, A. (1980). Stage analysis of reaction processes. In G. E. Stelmach & J. Requin (Eds.), *Tutorials in motor behavior* (pp. 331–354). North-Holland.

Spijkers, W. A., & Walter, A. (1985). Response processing stages in choice reactions. *Acta Psychologica*, *58*(2), 191–204.

Stöcker, C., & Hoffmann, J. (2004). The ideomotor principle and motor sequence acquisition: Tone effects facilitate movement chunking. *Psychological Research*, *68*(2–3), 126–137.

Thompson, V. A. (2013). Why it matters: The implications of autonomous processes for dual process theories—commentary on Evans & Stanovich (2013). *Perspectives on Psychological Science: A Journal of the Association for Psychological Science*, *8*(3), 253–256.

Wispinski, N. J., Gallivan, J. P., & Chapman, C. S. (2018). Models, movements, and minds: Bridging the gap between decision making and action. *Annals of the New York Academy of Sciences*, 1–22.

Zhu, F. F., Poolton, J. M., Wilson, M. R., Maxwell, J. P., & Masters, R. S. W. (2011). Neural co-activation as a yardstick of implicit motor learning and the propensity for conscious control of movement. *Biological Psychology*, *87*(1), 66–73.

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4.3 Article 3

Authors: Mengkai Luan, Heiko Maurer, Arash Mirifar, Jürgen Beckmann & Felix Ehrlenspiel

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Summary:

The present article investigated the influence of task-irrelevant action effects on motor sequence performance from a multiple-modality perspective. I compared motor sequence performances of participants who received different task-irrelevant action effects in an Auditory, Visual, or Audiovisual condition. In the Auditory condition, keypresses produced tones of a C-major scale that mapped to keys from left to right in ascending order. In the Visual condition, keypresses produced rectangles in different locations on the screen that mapped to keys from left to right in ascending order. In the Audiovisual condition, both tone and rectangle effects were produced simultaneously by keypresses. These results indicate that action effects with multiple sensory features facilitate the initiation and execution of motor sequences. The results imply that, compared to unimodal action effects, action effects from multiple sensory modalities can prime an action faster and strengthen associations between successive actions, leading to faster motor sequence performance.

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Multisensory action effects facilitate the performance of motor sequences

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Abstract

Research has shown that contingent, distinct action effects have a beneficial influence on motor sequence performance. Previous studies showed the beneficial influence of task-irrelevant action effects from one modality (auditory) on motor sequence performance, compared with no task-irrelevant action effects. The present study investigated the influence of task-irrelevant action effects on motor sequence performance from a multiple-modality perspective. We compared motor sequence performances of participants who received different task-irrelevant action effects in an auditory, visual, or audiovisual condition. In the auditory condition, key presses produced tones of a C-major scale that mapped to keys from left to right in ascending order. In the visual condition, key presses produced rectangles in different locations on the screen that mapped to keys from left to right in ascending order. In the audiovisual condition, both tone and rectangle effects were produced simultaneously by key presses. There were advantages for the audiovisual group in motor sequence initiation and execution. The results implied that, compared with unimodal action effects, action effects from multiple sensory modalities can prime an action faster and strengthen associations between successive actions, leading to faster motor sequence performance.

Keywords Motor sequence · Multisensory · Action effect · The ideomotor principle

When we act, we usually have a goal in mind—we write a manuscript with the goal of publishing our research, we reach for a glass of wine with the goal of drinking it, and we press "k" on the keyboard with the goal of it appearing on the monitor. The idea that these goals drive our actions—even motor actions—is the central tenet of the ideomotor principle (for a review, see Stock & Stock, 2004). Motor actions are generated to achieve desired goals, which are to bring intended and expected sensory effects (Hommel, 1996). Thus, sensory action effects are important parts of an action's mental representation (Kunde, Koch, & Hoffmann, 2004). Learning or performing a particular action requires the acquisition of associations between actions and their effects (Elsner & Hommel, 2001). Previous research has shown that anticipation of sensory action effects can prime the action (Kunde, 2001; Kunde et al., 2004), and also plays a crucial role in the acquisition and execution of motor sequences (Hoffmann, Sebald, & Stöcker, 2001; Stöcker & Hoffmann, 2004; Stöcker, Sebald, & Hoffmann, 2003). Previous studies on the influence of sensory action effects on motor sequence performance focused on the influence of a unimodal action effect. However, to our knowledge, the role of action effects from multiple sensory modalities perspective has hardly been investigated.

According to the ideomotor principle, sensory action effects are integrated parts of action representation, and an action is bidirectionally associated with action effects (Greenwald, 1970). Therefore, the sensory effects of an action may "prime" the execution of the action, if bidirectional associations between actions and their effects have been acquired. In a study by Elsner and Hommel (2001), during an acquisition phase, participants were free to press either the left or right key in response to a centrally presented visual signal.

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Each key, however, contingently triggered either a high or low tone. In the test phase, participants were asked to respond to these tone signals by pressing one of the same two keys. Participants responded faster to a tone if they had to press the key that had previously triggered that tone, compared with the other key. Further, when asked to freely choose which key to press in response to a tone, participants preferred to press the key that had previously triggered that tone.

More straightforwardly related to the assumption that anticipation of effects generates action, studies have also investigated whether predictable sensory effects still have an impact on an action despite following the action, and thus being retroactive. Studies on the response-effect compatibility have repeatedly shown this to be the case. For example, in a four-choice reaction time paradigm, participants responded faster when the responses' location spatially corresponded to the location of the responses' visual effects (one of four horizontally aligned boxes lit up on a monitor; task-irrelevant) than when locations did not spatially correspond. Additionally, in a two-choice task, participants initiated a certain force faster when the action triggered auditory effects of corresponding, rather than noncorresponding, intensity (Kunde, 2001). The response-effect compatibility effect has been reported for many task variations and relations between responses and effects (Koch & Kunde, 2002; Kunde, 2001, 2003; Kunde et al., 2004). Thus, although sensory effects are technically irrelevant when the actor only has to respond to a trigger stimulus and the effects follow this response, the effects or their anticipation still serve a function in selecting the response (Hommel, 2009).

Given that a significant amount of everyday behavior is structured in sequential succession, and our actions sequentially interact with effects in the environment, the role of anticipation of action effects has also been studied in relation to learning of movement sequences. Learning of movement sequences is often investigated within a serial reaction task (SRT) paradigm, wherein participants are asked to respond to successively presented stimuli, and each response triggers the next stimulus presentation. Hoffmann et al. (2001) found that task-irrelevant sensory effects from auditory modality, such as tone effects, influence the serial learning in SRT. The reaction time to ordered stimuli was faster for the experimental group with tone effects than for the control group without tone effects if tone effects irrelevant to the task were contingently mapped to the responses. Based on such findings, it has been argued that stable associations not only develop between responses and their effects but also between the successive effects themselves (Greenwald, 1970). Greenwald (1970) postulated that for sequence control, eventually the representation of the sequence of (anticipated) effects takes over response control. After repeatedly experiencing stimulus–response–effect triplets, sensory effect production leads to the anticipation of the next effect, which in turn triggers the next response. This process can be viewed as effect chaining; however, its consequences are less visible in the classic SRT task, as each response (also) occurs in response to a stimulus.

If an entire sequence needs to be learned and reproduced—for example, a piano melody—effect chaining should be more evident. In a study by Stöcker and Hoffmann (2004), participants learned two motor sequences: a short sequence of three ordered letters and a long sequence of six ordered letters. In one group of participants ("tone group"), each key press was followed by an immediate tone effect that was distinctively and contingently mapped to the key press. The tones were of the C-major scale and mapped to the keys from left to right, in ascending order. The other group of participants received no auditory effects ("no-tone group"). The two sequences were learned within an SRT paradigm, with each letter of a sequence first presented as a stimulus on a computer monitor, to which participants then responded, resulting in a contingent effect (or none), and after a short interval, the next letter of the sequence was presented. Additionally, a label on the screen always indicated which of the two sequences was presented. Performance was assessed within a choice reaction time paradigm. After the label indicating which sequence was to be executed (the short or the long sequence) appeared on the screen, participants were to correctly reproduce the whole sequence as quickly as possible. It was assumed that, compared with the no-tone group, effect chaining in the tone group would not only lead to faster reaction times but also facilitate associations of successive elements in the motor sequence and the chunking of the elements of the sequence into a larger unit. Based on the general finding that motor sequences with fewer elements are initiated faster than motor sequences with more elements (Verwey, 1999), the initiation times (ITs) of motor sequences would presumably be smaller in the tone than in the no-tone group. Results showed both motor sequences were initiated significantly faster in the tone group. This effect is associated with shorter interresponse times (IRTs; i.e., the transition between keys within a sequence) in the tone group than no-tone group. These findings supported that action–effect associations lead to faster initiation and execution of motor sequences.

Stöcker and Hoffmann (2004) showed a beneficial influence of the task-irrelevant action effects from one modality (auditory), compared with no auditory effects. The action effects in the original Stöcker and Hoffmann paradigm consisted of kinesthetic feedback from the fingers and proprioceptive perception of responses (Greenwald, 1970). When they are augmented by contingent sensory effects from an auditory modality (i.e., tones), all these sensory effects form the coherent action effects. The action effects from different modalities are coded into the action representation as different features of an event file in a distributed fashion (Hommel, 2004). These multimodal features are becoming effective retrieval cues or primes of the associated movement pattern. Numerous studies (e.g., Ladwig, Sutter, & Müsseler, 2013; Sedda, Monaco, Bottini, & Goodale, 2011; Zmigrod, Spapé, & Hommel, 2009) have provided evidence for interactions between features from different sensory modalities and between multisensory features and actions. Action effects from different modalities interact with each other, making the associations between action and effect and between successive actions appear to grow stronger (Kunde et al., 2004; Stöcker & Hoffmann, 2004). It may be speculated that the more action effect features are present and anticipated, the greater the activation of the representation of actions and the stronger the associations between successive actions. If this were the case, task-irrelevant action effects from multiple sensory modalities could prime the action more efficiently and make the associations between successive actions stronger than task-irrelevant action effects from a single sensory modality. Specifically, the initiation and execution of motor sequences would be faster in a condition with task-irrelevant action effects from multiple sensory modalities.

Thus, the purpose of the present study was to investigate the role of task-irrelevant action effects from a multisensory perspective and test whether there is an advantage for bimodal action effects, compared with unimodal action effects. The experimental design in this study was nearly identical to Stöcker and Hoffmann's (2004) paradigm, with the exception that different action effects were used. We compared motor sequence performance of participants who received different action effects in an auditory, visual, or audiovisual condition. Each participant practiced two motor sequences (short and long). The mapping of task-irrelevant action effects to key presses differed in each group. In the auditory condition, key presses produced tones of a C-major scale mapped to keys from left to right in ascending order (identical to the tone effects in Stöcker and Hoffmann's, 2004, paradigm). In the visual condition, key presses produced rectangles in different locations on the monitor mapped to keys from left to right in ascending order. In the audiovisual condition, both tone and rectangle effects were produced simultaneously by key presses. Initiation times (ITs) and mean interresponse times (mean IRTs) were measured as indicators for motor sequence performance. Action effects features in the audiovisual condition contained more action effect features than in the auditory or visual conditions. If task-irrelevant action effects from multiple modalities indeed prime actions more efficiently and strengthen associations between successive actions, the ITs and mean IRTs should be shorter in the audiovisual condition than in the other two conditions.

Methods

Participants

Sixty-seven healthy students between the ages of 18 and 26 years ($M = 24.5$ years, $SD = 2.4$ years; 32 men) took part in the experiment for extra credit. Due to reasons explained below, seven of participants were replaced. Three participants were replaced in the auditory group, two were replaced in the visual group, and two were replaced in the audiovisual group. Ultimately, each group consisted of 20 participants. All participants were right-handed with either normal or corrected-to-normal vision and normal hearing. Informed written consent was obtained from all participants prior to the experiment.

Apparatus and action effect

Stimuli were presented to participants on a 17-inch monitor using MATLAB 2017b, Psychtoolbox-3 controlled by a PC. The monitor was black and the instructions were in white, 20-point Times New Roman font. The spatial resolution of the monitor was set to 1,024 × 768 and the refresh rate was 60 Hz. The viewing distance was approximately 60 cm. An ASIO compatible sound card (LOGILINK PCI-Express 7.1) was used for high precision auditory timing. The output latency of the sound card was 5 ms. Participants rested their index, middle, and ring fingers of both hands on six keys ("s," "d," and "f" for the left hand, and "j," "k," "l" for the right hand) of a German QUERTZ-keyboard throughout the experiment. When a participant pressed any of the six keys, the respective response-effect associated with the key was immediately presented. In the auditory group, 80 ms of tones of a C-major scale ("c," "d," "e," "f," "g," and "a") were assigned to keys in ascending order from left to right. After a key press, the corresponding tone at an intensity of 60 dB (SPL) was immediately presented from two speakers positioned on the left and right sides of the monitor. In the visual group, the response keys were associated with six yellow rectangles (width: 79-pixel, height: 153-pixel). The rectangles appeared equally spaced on a vertically centered line, with the horizontal position assigned to the keys from left to right in ascending order without overlap, and each key press triggered the corresponding rectangle to flash on the monitor for 80 ms. In the audiovisual group, each key press simultaneously produced the key-specific tone effect of the auditory group and the key-specific rectangle effect of the visual group.

The action effect (tones or/and rectangles) was presented as soon as the corresponding key was pressed.

Procedure

The instructions for each experimental phase were displayed as text on the screen at the beginning of each phase. Throughout the experiment, participants placed their left index, middle, and ring fingers on the "f," "d," and "s" keys, and placed their right index, middle, and ring fingers on the "j," "k," and "l" keys.

The first phase was a short introductory phase (Phase 1), during which participants could get used to the action–effect relations by freely pressing the response keys and observing the key-press effects. The phase ended automatically after 120 seconds, or participants could end it whenever they wanted by pressing the spacebar. Usually, participants spent approximately 90–120 seconds on this phase.

In the second phase of the experiment (Phase 2), participants performed an SRT task with randomly ordered stimuli. One of the six letters was randomly presented in white, 20-point Times New Roman font at the center of the screen, and participants were asked to react as quickly as possible by pressing the key contingent to the stimulus. The corresponding action effect (tone, rectangle, or both), depending on the group, appeared when a key was pressed regardless of whether the response was correct. When an incorrect key was pressed, the word "Error" in a red, 20-point Arial font was presented for 50 ms at the bottom of the screen. The second phase consisted of two blocks of 60 trials each, and the response-to-stimulus interval (RSI) was set to 800 ms.

In the practice phase (Phase 3), participants were asked to learn two sequences that were labeled "X" and "Y." Sequence "X" was a short sequence consisting of three ordered letters (j-s-k), and sequence "Y" was a long sequence consisting of six ordered letters (s-j-f-k-d-l). In a typical trial in the practice phase, after the presentation of a white fixation cross for 1,500 ms in the middle of the screen, the sequence-specific cue (X or Y) was displayed at the center of the upper third of the screen (above the location of the boxes in the visual and audiovisual groups) and remained on the screen throughout each trial. The first letter of the sequence was simultaneously presented at the center of the screen. When a participant correctly pressed the corresponding key, the corresponding action effect (tone, rectangle, or both) appeared. After an RSI of 800 ms, the next stimulus was presented. This manipulation was to prevent participants from practicing very fast motor sequence production during this phase. When an incorrect key was pressed, the word "Error" was presented at the bottom of the screen for 50 ms in red, 20-point Arial font. However, an incorrect response always produced the action effect contingent on the pressed key. After completing the sequence, the sequence cue disappeared, and the next trial started. The practice phase consisted of two blocks containing 30 "X" sequence trials and 30 "Y" sequence trials. The sequence trials were presented in a randomized order across each block. After finishing each block, the error rate of the block was shown on the screen for 5 s. Participants were urged to concentrate on learning the sequences properly and not only respond to key-specific stimuli, since they would later have to reproduce the sequences based on sequence cue alone, without key-specific stimulus. They were also asked to focus more on accuracy than response speed.

In the test phase (Phase 4), participants were informed that speed and accuracy were now equally important for good performance. In each trial, only the sequence-specific cue ("X" or "Y") was presented after a white fixation cross was shown for 1,500 ms, after which participants were to type the whole sequence as quickly as possible. Each key press still produced the assigned action effect, regardless of whether the key press was correct. When an incorrect key press was made, the word "Error" flashed for 50 ms in red, 20-point Arial font at the same position as in the practice phase. Then, the fixation cross appeared, and the next trial started. Phase 4 consisted of six blocks of 60 sequence trials (30 "X" and 30 "Y"). The sequence trials were in a randomized order in each block. The error rate and mean IT of sequence typing for the block were shown on the screen for 5 s at the end of each block. There was a 30-second break between blocks. After the break, the next block could be started by pressing any key. For each trial, IT and IRTs were measured. IT was defined as the time between the onset of the sequence cue and the initial key press. IRTs were defined as the intervals between two contiguous key presses. IT and IRTs of trials with any errors were excluded from further analysis.

Data analysis

In the precursor study, Stöcker and Hoffmann (2004) did not report an effect size in their study; however, the effect size *f* can be calculated as 0.4 based on the statistical results and the number of participants in each group in this precursor study (in the precursor article, Stöcker & Hoffmann, 2004, showed that the ITs and mean IRTs for motor sequences in the group with auditory action effects were faster than the group without auditory action effects). The analysis of variance (ANOVA) of ITs data yielded $F(1, 38) = 8.69$, $p < .01$, which translates to an effect size (f) of 0.48. And the ANOVA of mean IRTs data yielded $F(1, 38) = 6.07$, $p < .05$, which translates to an effect size (f) of 0.4, using Lenhard and Lenhard's (2016) online calculator. The smaller of the two effect sizes (0.4) was selected for power analysis. Based on this, a prior power analysis using G*Power (Faul, Erdfelder, Lang, & Buchner, 2007) indicated that with a power level of .8, an alpha level of .05, and correlations between repeated measures of .5, a sample size of 39 (13 in each group) should be sufficient to reveal an effect of this magnitude. Stöcker and Hoffmann (2004), however, only showed the difference in motor sequence performance between conditions with and without auditory action effects. Whether the difference between conditions with action effects from multiple modalities and from a single modality would show similar magnitude, was not known before the current study. With the sample size used in the study (60 participants), effect sizes (*f*) higher than 0.41 can be detected with a power level of .8, an alpha level of .05, and correlations between repeated measures of .5 by a sensitivity analysis using G*Power (Faul et al., 2007).

Data processing and statistical analysis

Because action effects (tone, rectangle, or both) assigned to key presses were key contingent, an incorrect response always produced the action effect contingent on the pressed key, which deviated from the action effect sequence that the learned motor sequence entailed. Therefore, excessive error rates could lead to participants experiencing a different action effect sequence (Stöcker et al., 2003). To ensure comparability between the action effect sequences that participants within the same group experienced during the experiment, participants with error rates higher than 15% in Phase 4 were excluded and replaced (see Participants section). The error criterion of 15% was in line with Stöcker and Hoffmann (2004).

In Phase 3, error rates were reported as a measurement of sequence acquisition. We compared the error rates for the three action effect groups (auditory, visual, audiovisual) using the nonparametric Kruskal–Wallis test. In Phase 4, the median of ITs and mean IRTs (mean of IRTs within each sequence) computed for each factor combination were analyzed with mixed 3 (group) × 6 (block) × 2 (sequence) ANOVAs, with group as the between-subjects variable. Bonferroni-adjusted post hoc multiple comparisons were performed where there was a main effect of group (there were three pairwise comparisons; thus, *p* values were multiplied by three, with alpha = .05). A trend analysis was performed where there was a significant main effect of block, a significant Group × Block interaction effect, or a significant Sequence × Block interaction effect. Mauchly's test of sphericity was conducted before all analyses. We used the Greenhouse–Geisser correction to adjust degrees of freedom if the sphericity assumption was violated.

Results

Practice phase

The Kruskal–Wallis test found that the error rates in the three groups did not differ significantly, $\chi^2(2) = 1.00$, $p = .61$, indicating that there was no difference in sequence acquisition between groups. The mean error rates in the practice phase were 5.7% for the auditory group, 4.7% for the visual group, and 3.6% for the audiovisual group.

Test phase

Initiation times (ITs)

The ANOVA revealed a significant main effect of block, $F(2.29, 130.40) = 57.58$, $p < .001$, $\eta_p^2 = .50$. The trend analysis revealed both significant linear, $F(1, 57) = 82.07$, $p < .001$, $\eta_p^2 = .59$, and quadratic, $F(1, 57) = 66.86$, $p < .001$, $\eta_p^2 = .54$, trends, showing that ITs generally decreased with practice, but this effect is asymptotic with the relative decrease in ITs lessening with practice. The main effect of sequence was significant, $F(1, 57) = 23.64$, $p < .001$, $\eta_p^2 = .29$, showing that the ITs in the three-key sequence were shorter than in the six-key sequence. The Block × Sequence interaction was also significant for ITs, $F(2.42, 138.08) = 4.21$, $p = .012$, $\eta_p^2 = .07$. The trend analysis only revealed a significant linear trend, $F(1, 57) = 8.01$, $p = .006$, $\eta_p^2 = .12$, indicating that the difference of ITs between two sequences decreased with practice in a relatively constant, linear fashion. Notably, the main effect of group was significant, $F(2, 57) = 4.65$, $p = .013$, $\eta_p^2 = .14$. Bonferroni-adjusted post hoc multiple comparisons showed that ITs in the audiovisual group were significantly faster than in the other two groups (*ps* < .033). Additionally, the Group × Sequence interaction was significant, $F(2, 57) = 3.69$, $p = .031$, $\eta_p^2 = .12$, showing that the difference of ITs between two sequences was smaller in the audiovisual group than in the other groups (the differences between estimated marginal means for two sequences: auditory group, 74 ms; visual group, 97 ms; audiovisual group, 27 ms). The Group × Block interaction, $F(4.58, 130.40) = 2.02$, $p = .09$, and the three-way Group × Block × Sequence interaction, $F(4.85, 138.08) = 0.50$, $p = .77$, did not approach significance (see Fig. 1).

Mean interresponse times (mean IRTs)

The ANOVA showed a significant main effect of block, $F(2.92, 166.29) = 175.98$, $p < .001$, $\eta_p^2 = .76$. The trend analysis revealed both significant linear, $F(1, 57) = 311.93$, $p < .001$, $\eta_p^2 = .85$, and quadratic, $F(1, 57) = 111.02$, $p < .001$, $\eta_p^2 = .66$, trends, showing that mean IRTs generally decreased with practice, but this effect is asymptotic, with the relative decrease in mean IRTs lessening with practice. And the main effect of sequence was significant, $F(1, 57) = 31.68$, $p < .001$, $\eta_p^2 = .36$, indicating mean IRTs in the three-key sequence were shorter than in the six-key sequence. The Block × Sequence interaction was also significant for mean IRTs, $F(3.19, 181.82) = 16.93$, $p < .001$, $\eta_p^2 = .23$. The trend analysis revealed a significant linear trend, $F(1, 57) = 39.36$, $p < .001$, $\eta_p^2 = .41$, showing that the (negative) trend was stronger for the six-key sequence, which resulted in a gradual decrease in the difference of mean IRTs between the two sequences. The significant quadratic trend, $F(1, 57) = 5.80$, $p = .019$, $\eta_p^2 = .09$, indicated that the difference of mean IRTs between the two sequences decreased more notably during early blocks relative to late blocks in the test phase. Notably, the main effect of group was again significant, $F(2, 57) = 8.22$, $p =$

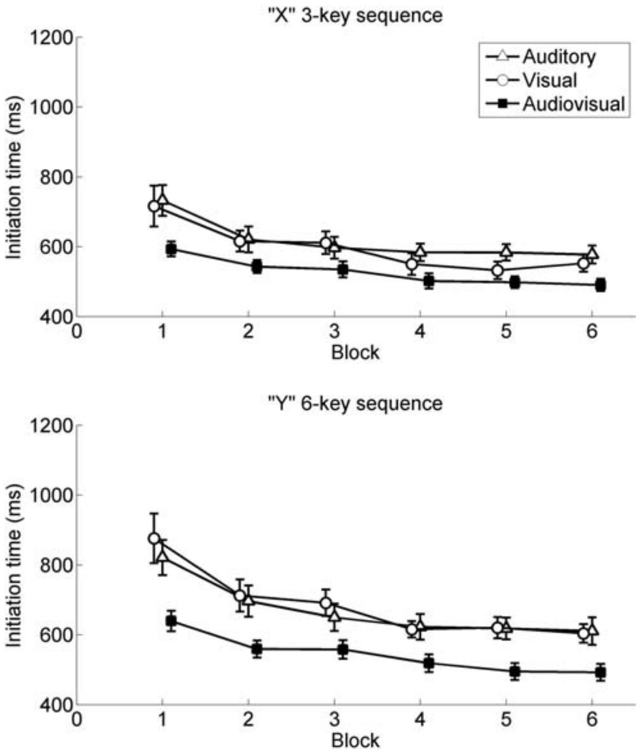

Fig. 1 Initiation times for both the "X" short sequence and "Y" long sequence, plotted over blocks in the test phase and divided by action effects. Error bars represent standard errors

.001, $\eta_p^2 = .22$. Bonferroni adjusted post hoc multiple comparisons showed that mean IRTs in the Audiovisual group were significantly faster than in the other two groups (*ps* < .003). Additionally, the Group × Block interaction was significant, $F(5.84, 166.29) = 4.47$, $p < .001$, $\eta_p^2 = .14$. The trend analysis only revealed a significant linear trend, $F(2, 57) = 8.33$, $p < .001$, $\eta_p^2 = .23$, indicating that the difference of mean IRTs between groups decreased with practice in a relatively constant, linear fashion. Neither the interaction of Group × Sequence, $F(2, 57) = 1.49$, $p = .23$, nor three-way Group × Block × Sequence interaction was significant, $F(6.38, 181.82) = 1.35$, $p = .23$[1] (see Fig. 2).

Discussion

The present study investigated the contribution of multisensory action effects in motor sequence performance. The task adapted from Stöcker and Hoffmann (2004) was to learn and perform two motor sequences under different action–effect conditions. We observed that compared with the groups with only auditory or visual action effects, there was an advantage in the ITs and mean IRTs performance for the group with audiovisual action effects. These results indicated that action effects with multiple sensory features facilitate the initiation and execution of motor sequences. To our knowledge, this study was the first to investigate the role of action effects on motor sequence performance from multiple sensory modalities perspective. This is an important area, because actions in daily life normally lead to multisensory action effects, including proprioception, vision, and audition, which leads to an activation of a broad network of different modalities (Esser & Haider, 2018).

ITs were significantly faster in the audiovisual group than the other groups, which suggests that motor sequence initiation was improved by providing more action effect features. Stöcker and Hoffmann (2004) showed that ITs were faster in a group with task-irrelevant auditory action effects than without auditory action effects. They argued that task-irrelevant auditory action effects facilitate the chunking of sequence elements into larger units. According to their reasoning, our results for ITs, therefore, indicate that action effects with more features facilitate the associations between successive elements and the further development of motor chunks. The so-called motor chunk is a representation linking a limited number of action elements, such as key presses, together (Klapp,

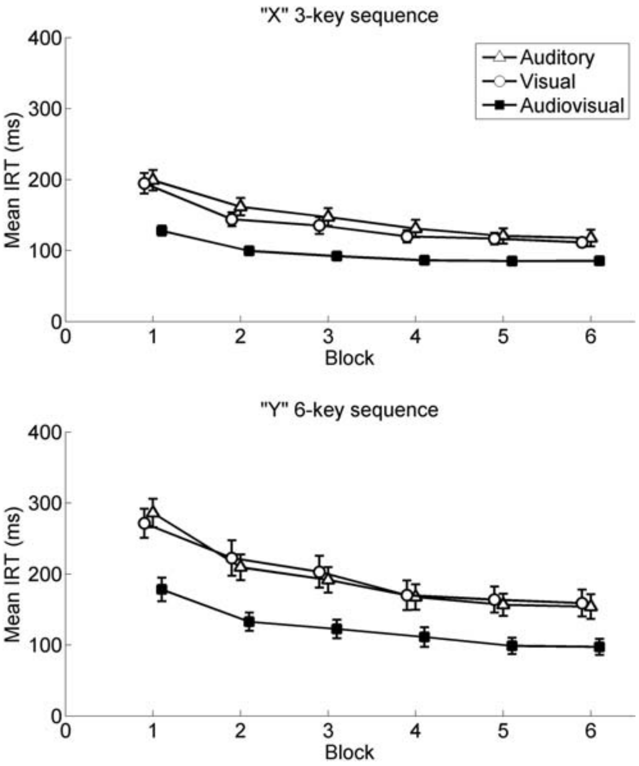

Fig. 2 Mean interresponse times for both the "X" short sequence and "Y" long sequence, plotted over blocks in the test phase and divided by action effects. Error bars represent standard errors

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[1] Here, the mean IRTs indicated the mean of all IRTs within each sequence (i.e., two IRTs of the three-key sequence and five IRTs of the six-key sequence). Following the advice of one reviewer, we also recalculated our main analysis of the IRTs data to only include the first two IRTs within each sequence (i.e., the first two IRTs of the three-key sequence and the first two IRTs of the six-key sequence). This proceeding did not alter any of the relevant results of the mean IRTs data (see online supplementary material).

1995; Sternberg, Monsell, Knoll, & Wright, 1978). As a result, these action elements can be selected as one single action element in a control hierarchy, leading to fast motor sequence initiation (Verwey, 1999). Following the ideomotor principle (Greenwald, 1970), when stimulus–response–effect triplets in the practice phase and response–effect pairs in the test phase are repeatedly experienced in the same order, action effects are first associated with the actions that produced them. Action effects of sequential actions are serially chained, and the associations between consecutive elements of the action–effect sequence are formed (Hoffmann et al., 2001; Stöcker & Hoffmann, 2004; Stöcker et al., 2003). The sequence representations contain not only representations of the actions themselves but also of the action effects associated with those actions (Stöcker & Hoffmann, 2004). It could be speculated that the more action effect features exist, the stronger the associations are between contiguous action effects in the effect sequence, leading to the development of a sequence representation of different quality.

It is worth noting that there was a significant interaction between sequence and group, showing that the sequence-length effect in the audiovisual group was smaller than in the other groups (i.e., the sequence-length effect was reduced by providing more action effect features). The sequence-length effect refers to the fact that the more elements the sequence has, motor sequence initiation takes longer. Reduction of the sequence-length effect is linked with the development of motor chunk (Verwey, 1999). Therefore, the reduction of the sequence length effect might support the chunking-based explanation. However, only one short and one long sequence were used in this study, which differed in several aspects besides their length (e.g. the hand starting the sequence). A more direct approach to control for this in future experiments would be to randomize sequences between participants.

Beyond movement initiation, our results regarding mean IRTs showed that providing more information of action effects from multiple modalities improve motor sequence execution. There are two interpretations based on ideomotor principle that are not mutually exclusive that can explain why this happens. First, as we discussed above, action effects with more features facilitate the development of motor chunks. Chunking also influences motor sequence execution (i.e., mean IRTs). Key presses following a motor chunk initiation can be prepared more easily and are typically fast. This is because these key presses only involve execution processes; these key presses have already been selected and prepared during the initiation of the motor chunk (Abrahamse, Ruitenberg, De Kleine, & Verwey, 2013). Therefore, execution of a motor sequence with a more effective chunking process would be faster. Second, representations of actions include their perceivable sensory action effects and the anticipation of these action effects should activate action control (Kunde, 2001). The more action effect features belong to an action representation, the more action effects are anticipated, which leads to greater activation of action representation (Elsner & Hommel, 2001), which in turn facilitates triggering of each individual key press. The action effects in the audiovisual group contained more effect features, the anticipation of the audiovisual action effects of an individual key press activated the representation of the key press greater, which accelerated the respective key press. Taken together, action effects in the audiovisual group may have reduced mean IRTs in two not mutually exclusive ways, by strengthening the associations between contiguous action effects and by evoking a greater activated representation of each individual key press.

The present design does not rule out potential alternative explanations, however, so that several theoretical possibilities might also account for the benefits from action effects with more features: First, several studies have demonstrated that when actions (e.g., pinches, button presses, tapping on a table) elicit a more reliable, higher quality feedback, action control is more effective (Neszmélyi & Horváth, 2017, 2018, 2019). In our study, the action effects in the audiovisual group might provide more reliable feedback than in other groups, allowing for more efficient motor control (Horváth, Bíró, & Neszmélyi, 2018). Thus, participants in the audiovisual group might be more confident in the success of the actions and can execute not only the subsequent actions within the motor sequence but also all subsequent sequences at a higher speed. Second, the present study measures sequence acquisition by error rates in the practice phase. It might be insensitive towards explicit sequence knowledge. Thus, there might be a difference in explicit sequence knowledge between groups. The evidence for the relevance of action effects for explicit knowledge of the motor sequence has been shown in several studies (Esser & Haider, 2018; Lustig & Haider, 2019; Tubau, Hommel, & López-Moliner, 2007). Tubau et al. (2007) found that response-contingent tone effects facilitate phonetic coding. Phonetic coding in turn increases the likelihood that participants enter a plan-based control mode and enhances the acquisition of explicit knowledge. Introducing visual effects might motivate an imagery-based planning strategy. And the action effects in the Audiovisual group might result in a planning strategy based on both phonetic codes and imagery codes, leading to more explicit knowledge of the motor sequence in the practice phase and better motor sequence performance in the test phase. Third, the beneficial influence of the multisensory action effects could be attributed to stimulus–effect learning. In this study, participants are required to learning the mapping of letters onto keys. The spatially arranged key locations share response–effect compatibility with action effects (Kunde, 2001; Stöcker et al., 2003). The action effects with more features might make it easier to map the required keys onto letters. Fourth, the benefit of multisensory effects might be individual differences. It might be easier for some participants to code auditory action effects into action representations while others might prefer to code the visual action effects. It will make it easier for them if they have a choice to select the modality in which the action effects are coded.

Some caution regarding the generality of the beneficial influence of multisensory action effects are warranted. One the one hand, all action effects in our study were contingently mapped to the response keys in ascending order from left to right. Numerous studies have shown that the impact of action effects on the action depends on the compatibility of the action–effect mapping (e.g., Hoffmann et al., 2001; Kunde, 2001, 2003; Stöcker & Hoffmann, 2004). The compatibility of the action–effect mapping of different modalities should be an important factor for observed ITs and mean IRTs enhancement from unimodal action effect to multisensory action effects. Mutual priming of effect codes would be harmed with a noncorresponding mapping for all modalities (Kunde et al., 2004). The benefits from action effects with more features could then not be found. On the other hand, the relative timing of action effect features from different modalities might another factor for observed ITs and mean IRTs enhancement from unimodal action effect to multisensory action effects. In this study, the auditory action effects (tones) and visual action effects (rectangles) were presented simultaneously in the audiovisual group. However, the processing times for participants were likely to differ for features coded in different modalities and there is (diverging) output latency of the soundcard and the monitor (Zmigrod & Hommel, 2013). There may be a temporal window, within which auditory action effects and visual action effects must fall, for the benefits from multisensory task-irrelevant action effects to motor sequences. With the current data, we cannot suggest the temporal principle and criterion of the beneficial influence of action effects from multiple modalities. Additional experiments are needed to elucidate these points.

Overall, the present study investigated the role of action effects on the motor sequence performance from a multiple-modality perspective. The findings suggest that task-irrelevant action effects from multiple sensory modalities indeed facilitates motor sequence performance more than task-irrelevant from a single sensory modality, leading to faster initiation and execution of motor sequences. One of the most concerning issues in multisensory research is whether information from different modalities is integrated into a coherent representation, or whether information from different sensory modalities is still processed separately. Previous studies have frequently revealed a so-called redundant signals effect (e.g., Diederich & Colonius, 2004; Miller, 1982), in which responses to unimodal (response) stimuli (i.e., preaction) are slower than responses to bimodal stimuli (i.e., when two stimuli from different modalities are presented simultaneously). Two explanations could account for the redundant signals effect: the race model and the coactivation model. According to the race model, a response is triggered by the stimulus detected first, making reaction time to bimodal stimuli faster than to unimodal stimuli by means of "statistical facilitation" (Raab, 1962). However, according to the coactivation model, units of information from different modalities might be integrated first, and the integration of information then triggers the response, which enables a faster response (Miller, 1982). Miller (1982) proposed a race model inequality test to distinguish the race model and the coactivation model. Building on the evidence of performance benefits of multisensory response cues (i.e., preaction), future research could investigate whether the benefits from multisensory task-irrelevant action effects (i.e., postaction) to motor sequences depend on the integration of information from multiple modalities. Furthermore, the research was based on motor sequences; thus, the ecological validity and practical implications of this study are limited. One previous study showed that performance of more complex actions (e.g., ball-tossing) can be primed and enhanced by contingent action effects (Land, 2018). An interesting question to be addressed by future research would be whether action effects with more features better facilitate complex human motor skills, as shown in augmented feedback studies (Effenberg, 2005; Marchal-Crespo, McHughen, Cramer, & Reinkensmeyer, 2010; Sigrist, Rauter, Riener, & Wolf, 2013).

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References

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

Diederich, A., & Colonius, H. (2004). Bimodal and trimodal multisensory enhancement: effects of stimulus onset and intensity on reaction time. *Perception & psychophysics, 66*(8), 1388-1404.

Effenberg, A. O. (2005). Movement sonification: Effects on perception and action. *IEEE Multimedia, 12*(2), 53–59.

Elsner, B., & Hommel, B. (2001). Effect anticipation and action control. *Journal of Experimental Psychology: Human Perception and Performance, 27*(1), 229–240.

Esser, S., & Haider, H. (2018). Action–effects enhance explicit sequential learning. *Psychological Research, 82*(6), 1113–1129.

Faul, F., Erdfelder, E., Lang, A.-G., & Buchner, A. (2007). G*Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior Research Methods, 39*(2), 175–191.

Greenwald, A. G. (1970). Sensory feedback mechanisms in performance control: With special reference to the ideo-motor mechanism. *Psychological Review, 77*(2), 73–99.

Hoffmann, J., Sebald, A., & Stöcker, C. (2001). Irrelevant response effects improve serial learning in serial reaction time tasks. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 27*(2), 470–482.

Hommel, B. (1996). The cognitive representation of action: Automatic integration of perceived action effects. *Psychological Research, 59*(3), 176–186.

Hommel, B. (2004). Event files: Feature binding in and across perception and action. *Trends in Cognitive Sciences, 8*(11), 494–500.

Hommel, B. (2009). Action control according to TEC (theory of event coding). *Psychological Research PRPF, 73*(4), 512–526.

Horváth, J., Bíró, B., & Neszmélyi, B. (2018). Action–effect related motor adaptation in interactions with everyday devices. *Scientific Reports, 8*(1), 1–8.

Klapp, S. T. (1995). Motor response programming during simple choice reaction time: The role of practice. *Journal of Experimental Psychology: Human Perception and Performance, 21*(5), 1015–1027.

Koch, I., & Kunde, W. (2002). Verbal response-effect compatibility. *Memory & Cognition, 30*(8), 1297–1303.

Kunde, W. (2001). Response-effect compatibility in manual choice reaction tasks. *Journal of Experimental Psychology: Human Perception and Performance, 27*(2), 387–394.

Kunde, W. (2003). Temporal response-effect compatibility. *Psychological Research, 67*(3), 153–159.

Kunde, W., Koch, I., & Hoffmann, J. (2004). Anticipated action effects affect the selection, initiation, and execution of actions. *The Quarterly Journal of Experimental Psychology Section A, 57*(1), 87–106.

Ladwig, S., Sutter, C., & Müsseler, J. (2013). Intra-and intermodal integration of discrepant visual and proprioceptive action effects. *Experimental Brain Research, 231*(4), 457–468.

Land, W. M. (2018). Priming of complex action via movement contingent sensory effects. *Human Movement Science, 61*, 135–143.

Lenhard, W., & Lenhard, A. (2016). Calculation of effect sizes [Computer software]. Retrieved from https://www.psychometrica.de/effect_size.html

Lustig, C., & Haider, H. (2019). Response-effects trigger the development of explicit knowledge. *Acta Psychologica, 194*, 87–100.

Marchal-Crespo, L., McHughen, S., Cramer, S. C., & Reinkensmeyer, D. J. (2010). The effect of haptic guidance, aging, and initial skill level on motor learning of a steering task. *Experimental Brain Research, 201*(2), 209–220.

Miller, J. (1982). Divided attention: Evidence for coactivation with redundant signals. *Cognitive Psychology, 14*(2), 247–279.

Neszmélyi, B., & Horváth, J. (2017). Consequences matter: Self-induced tones are used as feedback to optimize tone-eliciting actions. *Psychophysiology, 54*(6), 904–915.

Neszmélyi, B., & Horváth, J. (2018). Temporal constraints in the use of auditory action effects for motor optimization. *Journal of Experimental Psychology: Human Perception and Performance, 44*(11), 1815–1829.

Neszmélyi, B., & Horváth, J. (2019). The role of auditory context in action–effect-related motor adaptation. *Human Movement Science, 67*, 102503.

Raab, D. H. (1962). Division of psychology: Statistical facilitation of simple reaction times. *Transactions of the New York Academy of Sciences, 24*(5, Series II), 574–590.

Sedda, A., Monaco, S., Bottini, G., & Goodale, M. A. (2011). Integration of visual and auditory information for hand actions: Preliminary evidence for the contribution of natural sounds to grasping. *Experimental Brain Research, 209*(3), 365–374.

Sigrist, R., Rauter, G., Riener, R., & Wolf, P. (2013). Augmented visual, auditory, haptic, and multimodal feedback in motor learning: a review. *Psychonomic Bulletin & Review, 20*(1), 21–53.

Sternberg, S., Monsell, S., Knoll, R. L., & Wright, C. E. (1978). The latency and duration of rapid movement sequences: Comparisons of speech and typewriting. In G. E. Stelmach (Ed.), *Information processing in motor control and learning* (pp. 117–152). New York, NY: Academic Press.

Stock, A., & Stock, C. (2004). A short history of ideo-motor action. *Psychological Research, 68*(2/3), 176–188.

Stöcker, C., & Hoffmann, J. (2004). The ideomotor principle and motor sequence acquisition: Tone effects facilitate movement chunking. *Psychological Research, 68*(2/3), 126–137.

Stöcker, C., Sebald, A., & Hoffmann, J. (2003). The influence of response–effect compatibility in a serial reaction time task. *The Quarterly Journal of Experimental Psychology Section A, 56*(4), 685–703.

Tubau, E., Hommel, B., & López-Moliner, J. (2007). Modes of executive control in sequence learning: From stimulus-based to plan-based control. *Journal of Experimental Psychology: General, 136*(1), 43–63.

Verwey, W. B. (1999). Evidence for a multistage model of practice in a sequential movement task. *Journal of Experimental Psychology: Human Perception and Performance, 25*(6), 1693-1708.

Zmigrod, S., & Hommel, B. (2013). Feature integration across multimodal perception and action: A review. *Multisensory Research, 26*(1/2), 143–157.

Zmigrod, S., Spapé, M., & Hommel, B. (2009). Intermodal event files: Integrating features across vision, audition, taction, and action. *Psychological Research, 73*(5), 674–684.

5 General Discussion

The present dissertation focuses on the roles of attentional direction and action effects in motor skill performance and acquisition and tries to broaden the currently field of related research. The studies conducted within this dissertation project examine how the effects of different attentional direction change within individual with practice and investigates the role of action effects from multiple sensory modalities perspective.

5.1 Discussion on the role of attentional direction

To understand how the effects of different attentional conditions change as a function of practice, Article 1 examined the performance of motor sequences under two different dual-task conditions across practice, applying a longitudinal, intra-individual approach. Moreover, Article 1 also addressed whether the preparation phase and the execution phase of motor skill are affected differently. Building upon the results of RT in Article 1, Article 2 disentangled the effect of attentional direction on selection and initiation stages of motor sequence to further understand attentional direction's influence on the preparation phase.

5.1.1 Preparation phase

Results in Article1 and Article 2 suggest that at the beginning of practice, participants could more rapidly select the motor sequence to respond to a sequence label stimulus in the skill-focused dual-task condition than in the extraneous dual-task condition. However, with practice, the advantage of skill-focused attention for selecting the motor sequence diminished. This finding is in line with the idea that, at the beginning of practice, the control of the motor skill was based on declarative knowledge (i.e. explicit knowledge) of the motor skill and consciously attended to in real-time (Anderson, 1982, 1983; Beilock & Gray, 2012; Fitts & Posner, 1967). During early practice, participants selected the motor sequence to respond to a sequence label stimulus by searching and retrieving the explicit knowledge of the motor sequence (e.g.,"the serial letters of the motor sequence") from memory (Beilock & Gray, 2012). This search and retrieval processes required working memory engagement (Thompson, 2013). In dual-task situations, participants have to keep both tasks ready in working memory (Koch et al., 2018). Thus, participants had to maintain the secondary task requirement in working memory at the same time. The skill-focused dual-task required them to pay attention to execution, and the extraneous dual-task required them to shift attention away from execution and pay attention to an extraneous stimulus (Luan et al., 2020). During early practice, maintaining the requirement of paying attention to motor sequence execution in the working memory might require less effort and demand less cognitive resources than maintaining the requirement of paying attention to an extraneous stimulus, because the former fitted their natural inclination of the attentional direction (Marchant et al., 2009). Therefore, the searching and retrieving of declarative knowledge of motor sequences appear to have been faster in the skill focused dual-task condition on account of more cognitive resources available. Gradually, with practice, declarative knowledge of the motor sequence became part of the cognitive representation of the corresponding sequence label (Thompson, 2013). In this case, the motor sequence was selected in the context without requiring further cognitive processing and working memory. As a result, the motor sequence selection was not influenced by the dual-task conditions.

5.1.2 Execution phase

Both Article 1 and Article 2 suggest a generally superior execution performance of motor skill in the extraneous dual-task condition compared to the skill-focused dual-task condition, even during early practice. However, it is inconsistent with typical low-skilled performance in dual-task literature, that is, inexperienced performers display superior performance in the skill-focused dual-task condition relative to the extraneous dual-task condition. Three not mutually exclusive explanations can possibly explain why.

The first explanation might be the different cognitive resource demands of the concurrent cognitive tasks used in the two studies. In the skill-focused dual-task condition, the concurrent cognitive task was related to the execution of the motor sequence (Beilock et al., 2002; 2004; Diekfuss et al., 2017; Gray, 2004). Participants needed to monitor each keypress and focus on motor skill execution to judge whether a tone was presented with the keypress. This conscious type of motor control requires additional cognitive involvement related to the dual task while pressing each key before the presentation of the tone. Conversely, in the extraneous dual-task condition, the cognitive involvement was partly or completely allocated to tone identification, which is not related to the movement (Beilock et al., 2002; 2004; Diekfuss et al., 2017; Gray, 2004). Participants simply needed to identify the tone frequency whenever they heard a tone; there were no cognitive demands related to the dual task before the presentation of the tone. As a result, the IKIs before tone presentation were slower in the skill-focused dual-task condition than in the extraneous dual-task condition, leading to slower execution in the former condition in early blocks.

Second, given that motor sequence is itself generally a high-speed motor task, it appears that deciding with which keypress a tone is presented during such fast motor sequence execution is difficult and requires great attention even during early practice. At the beginning of practice, participants attend to components of motor skill execution (Masters, 1993) and use a consciously controlled approach to execute motor sequences (Anderson, 1982; Fitts & Posner, 1967). Although controlled attentional processes take time to execute (Posner & Snyder, 1975), the speed of motor sequence execution is still too fast for assessing the keypress according to tone in the skill-focused dual-task condition. Therefore, to assess the keypress correctly, participants might actively slow motor sequence execution in the skill-focused dual-task condition.

The third explanation might be the simplicity of the extraneous dual task used in the two studies. In Article 1, the analysis of the dual task performance showed that the performance of tone identification (extraneous) was generally better than key identification (skill-focused). From a skill acquisition and automaticity framework, extraneous dual-task impairment in novice performance results from lack of available attentional resources sufficient to support motor skill execution and dual-task performance concurrently (Beilock et al., 2004). The extraneous dual task used in the two studies presented only two possible tones. Arguably, such a simple design does not demand such substantial attentional resources as to prevent novices from attending to execution and to interfere with their motor skill execution (Gabbett & Abernethy, 2012). Thus, motor sequence can be executed without interruption by the extraneous dual task even at the beginning of practice.

Typically, psychological phenomena do not have a single “real” cause (Hommel & Colzato, 2017). This is true for motor skill performance in dual-task conditions. The findings of execution performance in Article 1 and Article 2 suggest that there is no universal explanation that can fully explain the performance patterns across skill levels exhibited in dual-task conditions. The motor skill execution in dual-task conditions seems to be influenced by a variety of factors, such as the direction of attention manipulated by dual tasks (i.e., concurrent cognitive tasks), the cognitive involvement demands and the difficulty level of dual tasks, the amount of practice, and the type of the motor skill.

5.2 Discussion on the role of action effects

To investigate the effect of task-irrelevant action effects on motor skill performance from a multiple-modality perspective, Article 3 compared motor sequence performances of participants who received different task-irrelevant action effects in an auditory, visual, or audiovisual condition.

5.2.1 Preparation phase

The results in Article 3 suggest that action effects with multiple sensory features facilitate the selection and/or initiation of motor sequences. Action effects with more features facilitate the associations between successive elements and the further development of motor chunks. The so-called motor chunk is a representation linking a limited number of action elements, such as keypresses, together (Klapp, 1995; Sternberg et al., 1978). As a result, these action elements can be selected as one single action element in a control hierarchy, leading to a fast motor sequence initiation (Verwey, 1999). Following the ideomotor principle (Greenwald, 1970), when stimulus-response-effect triplets and response–effect pairs are repeatedly experienced in the same order, action effects are first associated with the actions that produced them. Action effects of sequential actions are serially chained, and the associations between consecutive elements of the action-effect sequence are formed (Hoffmann et al., 2001; Stöcker & Hoffmann, 2004; Stöcker et al., 2003). The sequence representations contain not only representations of the actions themselves but also of the action effects associated with those actions (Stöcker & Hoffmann, 2004). It could be speculated that the more action effect features exist, the stronger the associations are between contiguous action effects in the effect sequence, leading to the development of a sequence representation of different quality.

5.2.2 Execution phase

Article 3 showed that providing more information of action effects from multiple modalities improve motor sequence execution. There are two interpretations based on ideomotor principle that are not mutually exclusive that can explain why this happens. First, action effects with more features facilitate the development of motor chunks. Chunking also influences motor sequence execution. Keypresses following a motor chunk initiation can be prepared more easily and are typically fast. This is because these keypresses only involve execution processes; these keypresses have already been selected and prepared during the initiation of the motor chunk (Abrahamse et al., 2013). Therefore, execution of a motor sequence with a more effective chunking process would be faster. Second, representations of actions include their perceivable sensory action effects, and the anticipation of these action effects should activate action control (Kunde, 2001). The more action effect features belong to an action representation, the more action effects are anticipated, which leads to greater activation of action representation (Elsner & Hommel, 2001), which in turn facilitates triggering of each individual keypress. The action effects in the Audiovisual group contained more effect features, the anticipation of the audiovisual action effects of an individual keypress activated the representation of the keypress greater, which accelerated the respective keypress. Taken together, action effects in the Audiovisual group may have facilitated motor sequence execution in two not mutually exclusive ways, by strengthening the associations between contiguous action effects and by evoking a greater activated representation of each individual keypress.

5.3 External and internal focus of attention

The studies conducted within this dissertation project appear to be related to the research on the effects of attentional focus instructions (Wulf, 2007, 2013). This line of studies examining the relationship between attention and motor skill performance has compared an internal focus of attention with an external focus of attention. In these studies, the internal focus of attention is defined as attention to one's own body movements during skill execution (e.g., movement of the hands), whereas the external focus of attention is defined as attention directed to the effect one's body movement has on the external environment, such as an apparatus or implement (e.g., the movement of the bat, Wulf, 2007, 2013). Evidence has amassed for the advantages of adopting an external focus of attention relative to an internal focus across skill levels (e.g., Ille et al., 2013; Wulf et al., 1998).

The results of execution performance in Article 1 and Article 2 appear to align well with research on the effects of attentional focus instructions. The distinction between internal and external, however, is somewhat orthogonal to the skill-focus vs. extraneous distinction. For example, in my studies, participants were asked to monitor which keystroke was accompanied by a tone in the skill-focused dual-task condition. It is not clear whether the instruction led participants to attend to moving their fingers, which could be considered as an internal focus, or to the keys to be pressed, which could be considered as an external focus (Zentgraf et al., 2009). And the definition of extraneous focus is different from the definition of externally focused attention. The term extraneous focus refers to the focus on the extraneous stimulus not directly involved in the execution, whereas the external focus refers to the focus on the movement effect related to the execution (Castaneda & Gray, 2007). Attention to irrelevant auditory stimuli that are not involved directly in motor sequence execution is not an externally focused attention.

Moreover, the advantages of focusing on the movement effects, as compared with focusing on the body movements, emphasize the influence that an action's intended effects can have on motor planning and motor control. Based on the ideomotor theory, action effects are important parts of an action's mental representation (Kunde et al., 2004). The anticipation of action effects is an essential component underlying actions (Kunde et al., 2007), which can prime the action or motor skill execution (Elsner & Hommel, 2001; Kunde, 2001; Kunde et al., 2004). An external focus of attention would bring about the anticipation of action effects, which primes the action whose distal effects are most consistent with the actual goal (Ford et al., 2007). Yet, because the ideomotor theory is relatively abstract, it does not specifically predict the differential effect of external focus on multisensory action effects versus unimodal action effects. More research using comparable tasks is needed, which might allow us to make testable predictions and draw any conclusions.

5.4 Limitations and future research

Some general limitations may warrant attention. Firstly, what is not clear is which skill level participants had already gained after the acquisition phase (Phase 2 in Article 1, Article 2), which consisted of 60 trials of each keying sequence so that participants memorized motor sequences. Although we set an 800-ms RSI to prevent participants from quickly executing the motor sequence, participants might still have gained some proficiency in motor skill (Luan et al., 2020). Perhaps, for motor skill execution, only novices or beginners without proficiency profit from directing attention to execution (e.g., Beilock et al., 2004; Gray, 2004). Future investigations should thus find a way to quantify levels of expertise across practice or consider a paradigm in which participants only acquire and memorize the declarative knowledge of motor sequences without any execution in the acquisition phase.

Secondly, as mentioned before, in Article 1 and Article 2, the skill-focused dual task did not give instructions specific enough to make sure whether it induced an internal (the moving fingers) or external focus (the key to be pressed). Future research, which hopes to link research using the dual-task methodology with research on external versus internal foci of attention, should operationalize skill-focused dual-task conditions in terms of an internal focus or external focus differently and give different attention conditions to movement effects and irrelevant environmental stimuli respectively.

Thirdly, in each study of this dissertation project, only one short and one long sequence were used. The differences in the two sequences and interkey interval difference between locations can be attributed to the hand starting the sequence and the use of particular fingers. Although these problems are canceled out when comparing performance in different dual-task conditions (Article1, Article 2) and performance in different action effect groups (Article 3), they would affect the interpretation of the results of interkey intervals in Article 1 and the sequence-length effect in the three articles. A more direct approach to prevent hand-specific and finger specific effects in future experiments would be to randomize sequences between participants, which could counterbalance the hand starting the sequence and make each finger occur equally often at each sequential location across participants.

Fourthly, this dissertation project is based on motor sequences; thus, the ecological validity and practical implications are limited. The reason why we used motor sequence in Article 1 and Article 2 is that participants are able to gain proficiency in motor sequence in a relatively short time, enabling us to observe how the effects of dual tasks change as a function of practice skill level in a short period. Beilock et al. (2002) found that the nondominant foot of skilled players was controlled differently than their dominant foot, suggesting that for complex motor skills, proficiency is not acquired over a few days or weeks of practice. The course of the change of dual tasks' effects in complex motor skill requires further examination. Moreover, regarding the influence of action effects, some previous studies showed that the performance of more complex actions (e.g., ball-tossing) can be primed and enhanced by contingent action effects (Land, 2016, 2018). An interesting question to be addressed by future research would be whether action effects with more features better facilitate complex human motor skills.

6 Conclusion

This dissertation examines the effects of different attentional directions and multisensory action effects on motor skill performance across practice. The findings related to attentional directions suggest that the effects of attentional directions depend not only on the amount of practice but also on the stage of information processing. These findings further our knowledge of the effects of attentional directions. And this knowledge will help enhance training design by providing the most appropriate instruction on the attention direction according to the skill level and the stage of information processing. The findings related to action effects suggest that action effects from multiple sensory modalities indeed facilitate motor skill performance more than action effects from a single sensory modality. These findings make an important step towards practical application of movement-effect training paradigms to more common and practical motor skills. However, this dissertation project is based on the performance of relatively simple actions (keypresses) and movement sequences (motor sequences), and only analyzes the behavior data. Future research that incorporates not only complex human motor skills with high ecological validity but also information on brain oscillatory activity will provide a more complete picture.

7 References

Abernethy, B. (1988). Dual-task methodology and motor skills research: some applications and methodological constraints. *Journal of Human Movement Studies, 14*(3), 101-132.

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

Anderson, J. R. (1982). Acquisition of cognitive skill. *Psychological review, 89*(4), 369-406.

Anderson, J. R. (1983). The architecture of cognition: Cambridge, MA: Harvard University Press.

Beilock, S. L., Bertenthal, B. I., McCoy, A. M., & Carr, T. H. (2004). Haste does not always make waste: Expertise, direction of attention, and speed versus accuracy in performing sensorimotor skills. *Psychonomic Bulletin & Review, 11*(2), 373-379.

Beilock, S. L., & Carr, T. H. (2001). On the fragility of skilled performance: What governs choking under pressure? *Journal of Experimental Psychology: General, 130*(4), 701-725.

Beilock, S. L., Carr, T. H., MacMahon, C., & Starkes, J. L. (2002). When paying attention becomes counterproductive: impact of divided versus skill-focused attention on novice and experienced performance of sensorimotor skills.

Journal of Experimental Psychology: Applied, 8(1), 6-16.

Beilock, S. L., & Gray, R. (2012). From attentional control to attentional spillover: A skill-level investigation of attention, movement, and performance outcomes. *Human movement science, 31*(6), 1473-1499.

Castaneda, B., & Gray, R. (2007). Effects of focus of attention on baseball batting performance in players of differing skill levels. *Journal of Sport and Exercise Psychology, 29*(1), 60-77.

Diekfuss, J. A., Ward, P., & Raisbeck, L. D. (2017). Attention, workload, and performance: A dual-task simulated shooting study. *International Journal of Sport and Exercise Psychology, 15*(4), 423-437.

Dudman, J. T., & Krakauer, J. W. (2016). The basal ganglia: from motor commands to the control of vigor. *Current opinion in neurobiology, 37*, 158-166.

Elsner, B., & Hommel, B. (2001). Effect anticipation and action control. *Journal of Experimental Psychology: Human Perception and Performance, 27*(1), 229-240.

Fitts, P. M., & Posner, M. I. (1967). *Human performance.* Brooks/Cole.

Ford, P., Hodges, N. J., & Williams, A. M. (2005). Online attentional-focus manipulations in a soccer-dribbling task: Implications for the proceduralization of motor skills. *Journal of motor behavior, 37*(5), 386-394.

Ford, P., Hodges, N. J., & Williams, A. M. (2007). Examining action effects in the execution of a skilled soccer kick by using erroneous feedback. *Journal of motor behavior, 39*(6), 481-490.

Gabbett, T. J., & Abernethy, B. (2013). Expert–novice differences in the anticipatory skill of rugby league players. *Sport, Exercise, and Performance Psychology, 2*(2), 138-155.

Gray, R. (2004). Attending to the execution of a complex sensorimotor skill: expertise differences, choking, and slumps. *Journal of Experimental Psychology: Applied, 10*(1), 42-54.

Greenwald, A. G. (1970). Sensory feedback mechanisms in performance control: with special reference to the ideo-motor mechanism. *Psychological review, 77*(2), 73-99.

Hoffmann, J., Sebald, A., & Stöcker, C. (2001). Irrelevant response effects improve serial learning in serial reaction time tasks. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 27*(2), 470-482.

Hommel, B. (1996). The cognitive representation of action: Automatic integration of perceived action effects. *Psychological Research, 59*(3), 176-186.

Hommel, B. (2004). Event files: Feature binding in and across perception and action. *Trends in cognitive sciences, 8*(11), 494-500.

Hommel, B. (2009). Action control according to TEC (theory of event coding). *Psychological Research PRPF, 73*(4), 512-526.

Hommel, B., & Colzato, L. S. (2017). The grand challenge: Integrating nomothetic and ideographic approaches to human cognition. *Frontiers in Psychology, 8*, 100.

Hommel, B., Müsseler, J., Aschersleben, G., & Prinz, W. (2001). The theory of event coding (TEC): A framework for perception and action planning. *Behavioral and brain sciences, 24*(5), 849-878.

Ille, A., Selin, I., Do, M.-C., & Thon, B. (2013). Attentional focus effects on sprint start performance as a function of skill level. *Journal of Sports Sciences, 31*(15), 1705-1712.

Jackson, R. C., Ashford, K. J., & Norsworthy, G. (2006). Attentional focus, dispositional reinvestment, and skilled motor performance under pressure. *Journal of Sport and Exercise Psychology, 28*(1), 49-68.

Klapp, S. T. (1995). Motor response programming during simple choice reaction time: The role of practice. *Journal of Experimental Psychology: Human Perception and Performance, 21*(5), 1015-1027.

Koch, I., & Kunde, W. (2002). Verbal response-effect compatibility. *Memory & cognition, 30*(8), 1297-1303.

Koch, I., Poljac, E., Müller, H., & Kiesel, A. (2018). Cognitive structure, flexibility, and plasticity in human multitasking—An integrative review of dual-task and task-switching research. *Psychological bulletin, 144*(6), 557-583.

Kunde, W. (2001). Response-effect compatibility in manual choice reaction tasks. *Journal of Experimental Psychology: Human Perception and Performance, 27*(2), 387-394.

Kunde, W. (2003). Temporal response-effect compatibility. *Psychological Research, 67*(3), 153-159.

Kunde, W., Elsner, K., & Kiesel, A. (2007). No anticipation–no action: the role of anticipation in action and perception. *Cognitive Processing, 8*(2), 71-78.

Kunde, W., Koch, I., & Hoffmann, J. (2004). Anticipated action effects affect the selection, initiation, and execution of actions. *The Quarterly Journal of Experimental Psychology Section A, 57*(1), 87-106.

Ladwig, S., Sutter, C., & Müsseler, J. (2013). Intra-and intermodal integration of discrepant visual and proprioceptive action effects. *Experimental Brain Research, 231*(4), 457-468.

Land, W. M. (2016). Action effects and task knowledge: The influence of anticipatory priming on the identification of task-related stimuli in experts. *PLoS One, 11*(6), e0156928.

Land, W. M. (2018). Priming of complex action via movement contingent sensory effects. *Human movement science, 61*, 135-143.

Leavitt, J. (1979). Cognitive demands of skating and stickhandling in ice hockey. *Canadian journal of applied sport sciences. Journal canadien des sciences appliquees au sport, 4*(1), 46-55.

Luan, M., Mirifar, A., Beckmann, J., & Ehrlenspiel, F. (2020). The Varying Effects of Dual Tasks on the Performance of Motor Skills across Practice. *Journal of motor behavior*.

Marchant, D. C., Clough, P. J., Crawshaw, M., & Levy, A. (2009). Novice motor skill performance and task experience is influenced by attentional focusing instructions and instruction preferences. *International Journal of Sport and Exercise Psychology, 7*(4), 488-502.

Masters, R., Polman, R. C., & Hammond, N. (1993). ‘Reinvestment’: A dimension of personality implicated in skill breakdown under pressure. *Personality and individual differences, 14*(5), 655-666.

Nicolson, R., & Fawcett, A. (1990). Automaticity: A new framework for dyslexia research? *Cognition, 35*(2), 159-182.

Nissen, M. J., & Bullemer, P. (1987). Attentional requirements of learning: Evidence from performance measures. *Cognitive psychology, 19*(1), 1-32.

Posner, M., & Snyder, C. (1975). *Attention and cognitive control.* Information processing and cognition: The Loyola symposium: Hillsdale NJ: Erlbaum.

Rhodes, B. J., Bullock, D., Verwey, W. B., Averbeck, B. B., & Page, M. P. (2004). Learning and production of movement sequences: Behavioral, neurophysiological, and modeling perspectives. *Human movement science, 23*(5), 699-746.

Sedda, A., Monaco, S., Bottini, G., & Goodale, M. A. (2011). Integration of visual and auditory information for hand actions: preliminary evidence for the contribution of natural sounds to grasping. *Experimental Brain Research, 209*(3), 365-374.

Shin, Y. K., Proctor, R. W., & Capaldi, E. J. (2010). A review of contemporary ideomotor theory. *Psychological bulletin, 136*(6), 943-974.

Sternberg, S., Monsell, S., Knoll, R. L., & Wright, C. E. (1978). The latency and duration of rapid movement sequences: Comparisons of speech and typewriting *Information processing in motor control and learning* (pp.

117-152): Elsevier.

Stock, A., & Stock, C. (2004). A short history of ideo-motor action. *Psychological Research, 68*(2-3), 176-188.

Stöcker, C., & Hoffmann, J. (2004). The ideomotor principle and motor sequence acquisition: Tone effects facilitate movement chunking. *Psychological Research, 68*(2-3), 126-137.

Stöcker, C., Sebald, A., & Hoffmann, J. (2003). The influence of response–effect compatibility in a serial reaction time task. *The Quarterly Journal of Experimental Psychology Section A, 56*(4), 685-703.

Thompson, V. A. (2013). Why it matters: The implications of autonomous processes for dual process theories—Commentary on Evans & Stanovich (2013). *Perspectives on Psychological Science, 8*(3), 253-256.

Verwey, W. B. (1999). Evidence for a multistage model of practice in a sequential movement task. *Journal of Experimental Psychology: Human Perception and Performance, 25*(6), 1693-1708.

Wulf, G. (2007). Attentional focus and motor learning: A review of 10 years of research. *E-journal Bewegung und Training, 1*(2-3), 1-11.

Wulf, G. (2013). Attentional focus and motor learning: a review of 15 years. *International Review of Sport and Exercise Psychology, 6*(1), 77-104.

Wulf, G., Höß, M., & Prinz, W. (1998). Instructions for motor learning: Differential effects of internal versus external focus of attention. *Journal of motor behavior, 30*(2), 169-179.

Zentgraf, K., Lorey, B., Bischoff, M., Zimmermann, K., Stark, R., & Munzert, J. (2009). Neural correlates of attentional focusing during finger movements: A fMRI study. *Journal of motor behavior, 41*(6), 535-541.

Ziessler, M. (1998). Response–effect learning as a major component of implicit serial learning. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 24*(4), 962-978.

Ziessler, M., & Nattkemper, D. (2001). Learning of event sequences is based on response-effect learning: further evidence from a serial reaction task. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 27*(3), 595-613.

Zmigrod, S., Spapé, M., & Hommel, B. (2009). Intermodal event files: Integrating features across vision, audition, taction, and action. *Psychological Research PRPF, 73*(5), 674-684.

8 Appendix

8.1 List of Publications and Submissions

Luan, M., Mirifar, A., Beckmann, J., & Ehrlenspiel, F. (2020). The Varying Effects of Dual Tasks on the Performance of Motor Skills across Practice. *Journal of Motor Behavior*. doi:10.1080/00222895.2020.1828797

Luan, M., Maurer, H., Mirifar, A., Beckmann, J., & Ehrlenspiel, F. (2020). Multisensory action effects facilitate the performance of motor sequences. *Attention, Perception, & Psychophysics*. doi: 10.3758/s13414-020-02179-9

Hähl, W., Mirifar, A., Luan, M., & Beckmann, J. (2020). Dealing with failure: Prefrontal asymmetry predicts affective recovery and cognitive performance. *Biological Psychology*, *155*, 107927. doi:10.1016/j.biopsycho.2020.107927

Luan, M., & Mirifar, A. (2021). The Effect of Attentional Direction on Sub-Stages of Preparing for Motor Skill Execution Across Practice. *Perceptual and Motor Skills, 128*(3), 1292-1309. doi: 10.1177/00315125211009026

Mirifar, A., Luan, M., Beckmann, J., & Ehrlenspiel, F. (under review). Effects of Unilateral Dynamic Handgrip on Reaction Time and Error Rate. *Journal of Motor Behavior*.

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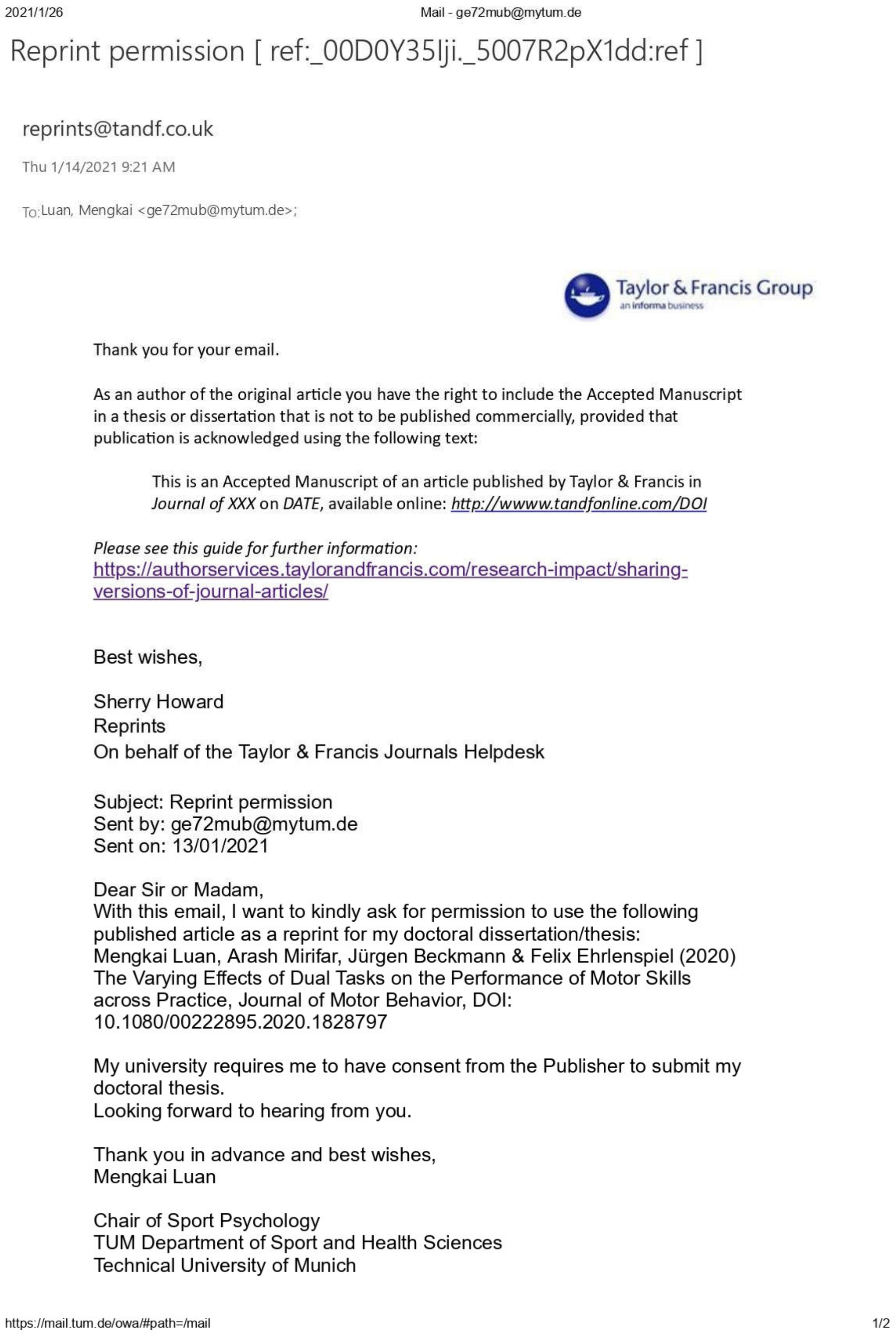

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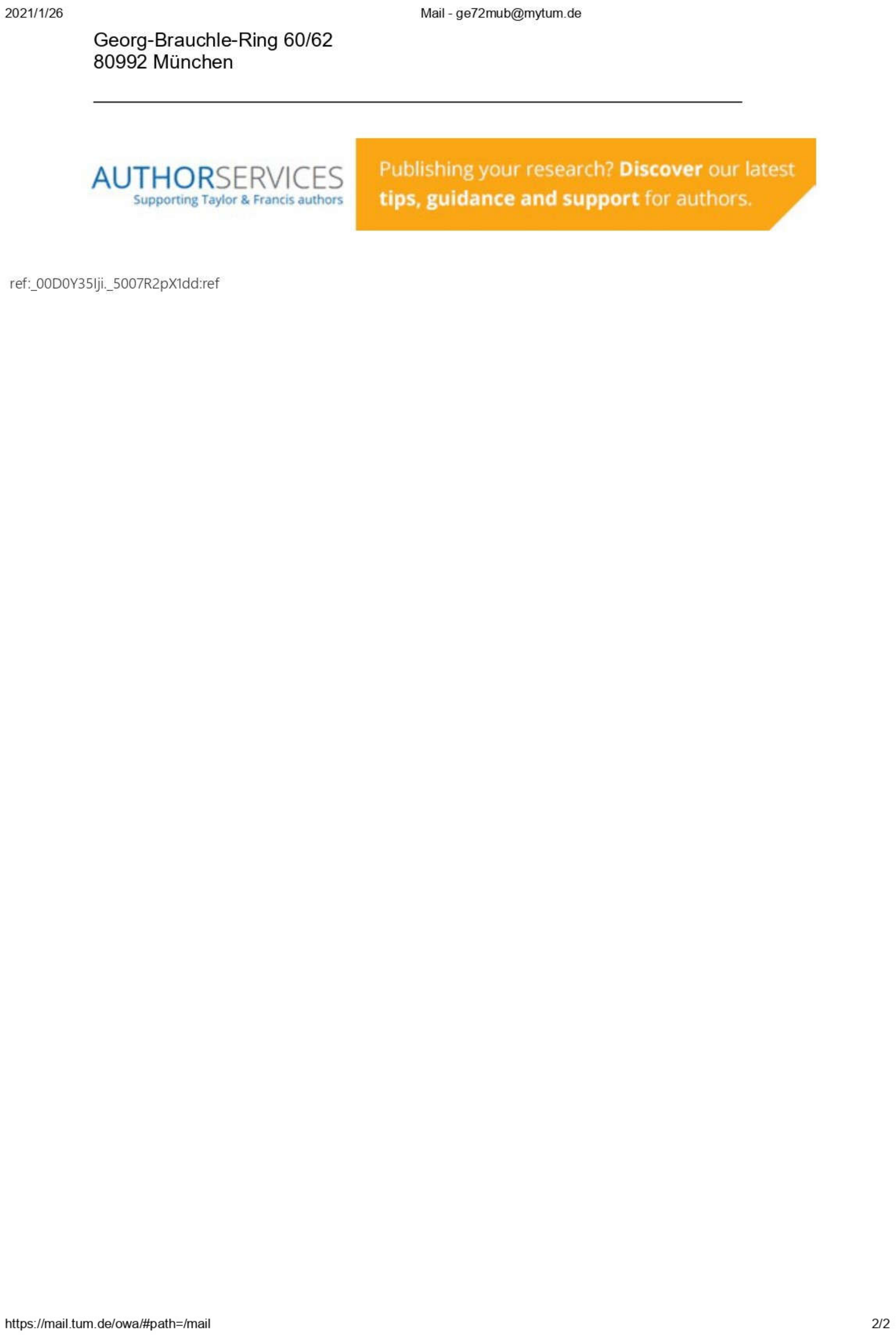

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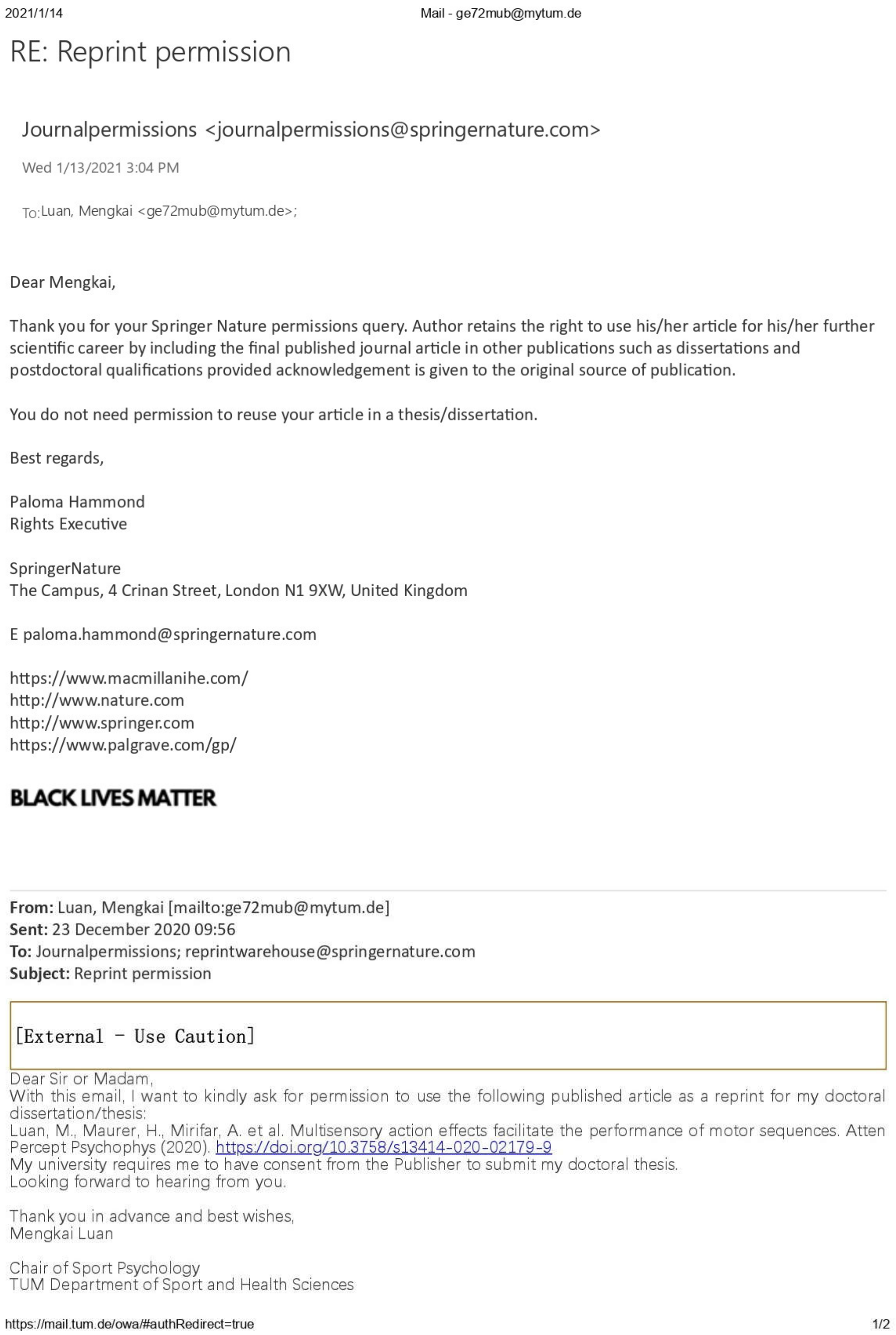

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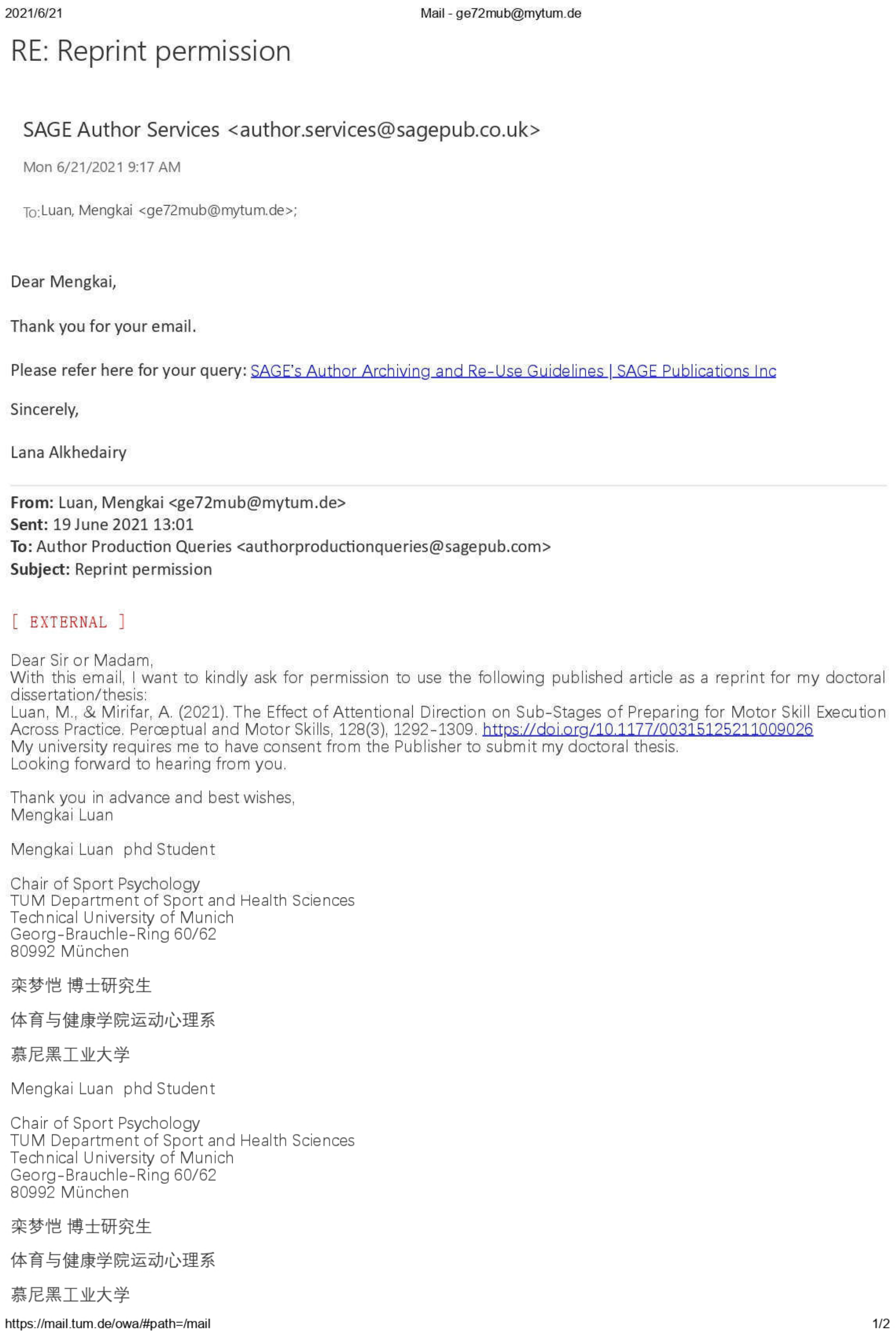

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