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MULTISENSORY INTEGRATION IN COMPLEX RHYTHMIC MOTOR TASKS

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ZUSAMMENFASSUNG

Für die erfolgreiche Ausführung verschiedenster motorischer Aufgaben scheint die Integration visueller und auditiver Informationen von besonderer Bedeutung zu sein. Ausgehend von dieser Annahme, wurden im Rahmen dieser publikationsbasierten Dissertation insgesamt drei empirische Studien durchgeführt, um das multisensorische Zusammenspiel visueller und auditiver Einflüsse bei der Bewältigung rhythmisch-motorischer Aufgaben eingehender zu betrachten.

Am Beispiel des Weitsprungs als komplexe rhythmisch-motorische Aufgabe wurde innerhalb der ersten Studie zunächst das *visuelle* Regulationsverhalten mithilfe feldbasierter Blickbewegungsaufzeichnungen untersucht. In bisherigen Forschungsarbeiten, die sich mit dem Schrittverhalten während des Weitsprunganlaufs auseinandersetzten, konnte ein universeller Punkt identifiziert werden, an dem die Schrittvariabilität stark zu sinken beginnt. Dieser Parameter wurde fortan mit dem Beginn des visuellen Regulationsprozesses gleichgesetzt, ohne jedoch das tatsächliche visuelle Verhalten der Akteure betrachtet zu haben. Das Ziel der ersten Studie bestand demnach darin, zu überprüfen, ob die entsprechende Anpassung des Schrittverhaltens mit einer Veränderung des Blickverhaltens einhergeht. Im Ergebnis zeigte sich, dass der Beginn der längsten Fixation auf das Absprungbrett als visueller Regulationsindikator des Blickverhaltens mit dem etablierten Schrittparameter zeitlich koinzidierte. In Anbetracht der Tatsache, dass der schrittbasierte visuelle Regulationsparameter mit einer Reduktion der Schrittvariabilität einherzugehen scheint und gegeben, dass gegenwärtige Forschungsarbeiten zu Blickbewegungen nahelegen, dass Fixationen von längerer Dauer zu besseren motorischen Leistungen führen können, kann nun angenommen werden, dass die längste Fixation auf das Absprungbrett einem ähnlichen Zweck dienen könnte.

Während innerhalb der ersten empirischen Untersuchung das visuelle Regulationsverhalten beim Weitsprunganlauf genauer charakterisiert werden konnte, blieb der Einfluss anderer Modalitäten dabei weitestgehend unberücksichtigt. Immer mehr aktuelle Forschungsarbeiten weisen jedoch darauf

hin, dass neben visuellen Informationen auch auditive Informationen für die Ausführung motorischer Aufgaben von großer Bedeutung sein können. Demnach stand innerhalb der zweiten empirischen Studie dieser Arbeit der Einfluss *auditiver* Informationen sowie deren Interaktion mit visuellen Informationen bei der Ausführung des Weitsprunganlaufs im besonderen Fokus. Innerhalb von zwei Experimenten wurden dafür unterschiedliche auditive Manipulationen, d.h., auditive Deprivation und Verzögerung des auditiven Feedbacks, in das experimentelle Design implementiert, um etwaige Auswirkungen auf das Schritt- und Blickverhalten sowie die Sprungleistung untersuchen zu können. Die auditiven Manipulationen zeigten gegensätzliche Ergebnisse. Während die Wegnahme auditiver Informationen zu einem stabileren Schritt- und Blickverhalten führte, ohne sich auf die erreichte Sprungweite auszuwirken, führte die Verzögerung auditiver Informationen zu einem deutlich variableren Schritt- und auch Blickverhalten sowie zu einer Verringerung der Sprungweite.

Die Ergebnisse des ersten Experiments der zweiten Studie weisen darauf hin, dass auditive Informationen für die erfolgreiche Ausführung des Weitsprunganlaufs nicht zwingend notwendig zu sein scheinen, während die Ergebnisse des zweiten Experiments nahelegen, dass verzögerte auditive Informationen einen Einfluss auf das visuelle Verhalten ausüben, wodurch sich wiederum Beeinträchtigungen im Schrittverhalten ergeben haben. Eine Erklärung für diese Befunde liegt möglicherweise in der Modality Appropriateness Hypothesis (MAH), welche besagt, dass die verlässlichste Modalität die Wahrnehmung innerhalb eines multisensorischen Kontexts dominiert. Entsprechend dieser Hypothese und im Einklang mit den Ergebnissen des zweiten Experiments, könnte der Weitsprung als eine motorische Aufgabe charakterisiert werden, für die die visuelle Modalität die höchste Verlässlichkeit aufzeigt, während der Einfluss anderer (d.h., weniger verlässlicher) Modalitäten eher von geringerer Bedeutung zu sein scheint. Die negativen Effekte der auditiven Verzögerung innerhalb des dritten Experiments könnten dagegen als eine Konsequenz der beeinträchtigten dominanten visuellen Modalität zu bewerten sein.

Ausgehend von diesen Ergebnissen sollte die MAH innerhalb einer dritten, kontrollierten Laborstudie weiter ergründet werden. Während visuelle

Informationen verlässlicher in der räumlichen Wahrnehmung sind, wird auditiven Informationen eine höhere Verlässlichkeit in der zeitlichen Wahrnehmung zugeschrieben. Entsprechend sollte sich die bisherige Dominanz der visuellen Modalität bei Veränderung der Anforderungen an die motorische Aufgabe umdrehen. Aus diesem Grund wurde für die letzte Studie die Aufgabe der Rhythmusreproduktion gewählt, da sie den Annahmen der MAH entsprach und besser innerhalb der auditiven Modalität gelöst wird. Um zu untersuchen, ob unimodale Stimulation in einer durch eine bestimmte Modalität dominierten Aufgabe für die erfolgreiche Aufgabenbewältigung ausreichend ist oder ob sich durch multimodale Stimulation (d.h., zusätzliche sensorische Informationen) Vorteile ergeben, sollten (visuell vs. auditiv vs. audiovisuell) dargebotene Rhythmen zeitlich so genau wie möglich reproduziert werden. Wie erwartet, war die Genauigkeit der Reproduktionen am höchsten, wenn auditive Informationen zur Verfügung standen und am geringsten in der visuellen Bedingung. Weiterhin zeigten sich keine Unterschiede zwischen auditiver und audiovisueller Stimulation, was darauf schließen lässt, dass die visuellen Informationen im Wesentlichen nicht zur Lösung der Aufgabe beigetragen haben. Wie von der MAH vorhergesagt, dominierte somit die verlässlichste Modalität die Wahrnehmung innerhalb eines multisensorischen Kontexts. Zusammenfassend lässt sich aus den Ergebnissen der Experimentalreihe schließen, dass in Abhängigkeit von einer gegebenen Aufgabenstruktur nicht alle zur Verfügung gestellten Informationsquellen gleichwertig genutzt werden.

SUMMARY

This publication-based thesis aimed to shed further light on the contributions of visual and auditory information to the execution of complex rhythmic motor tasks. To this end, a series of three empirical studies was designed.

The first two studies were conducted in the experimental setting of long jumping – a task that does not only require high precision but also high velocity to leap as far as possible. Within the first study, we aimed to examine visual regulation during the long jump run-up using portable eye-tracking technology. Previous research on the topic of visual regulation in long jumping has identified a universal instance in participants' gait behavior which introduces a rapid decrease in step variability. Since then, this parameter was considered synonymous with the (gait-based) onset of visual regulation. However, an investigation of actual visual behavior by means of direct measures was still pending to date. Hence, the first study was designed to identify a potential equivalent to the gait-based parameter within participants' gaze behavior. Results revealed that the moment of the longest gaze on the take-off board coincided with the occurrence of the well-established gait parameter. Given that i) the gait-based visual regulation parameter has been associated with a reduction in footfall variability and ii) current research advocates the idea that fixations of longer duration facilitate motor actions, one might speculate that the longest gaze on the take-off board might as well serve the reduction of movement variability.

While the parameter of visual regulation could be characterized in more detail within the first empirical investigation, the impact of other modalities has been neglected so far. However, current research is promoting the idea that, apart from visual information, auditory information might as well be crucial for the execution of motor tasks. For this reason, the second study of this thesis was designed to investigate the impact of auditory information as well as audiovisual interactions on the execution of the long jump run-up. To this end, two experiments were conducted implementing the auditory manipulations of auditory deprivation and delayed auditory feedback to identify the effects of auditory feedback on participants' gait and gaze behavior as well as their jumping

performance. Both manipulations revealed some contrasting results. That is, the auditory deprivation led to more stable gait and gaze patterns without any effect on jumped distance. On the contrary, the delayed auditory feedback led to more variable gait and gaze patterns and a decrease in participants' jumped distance.

The findings of the first experiment of the second study indicate that auditory information might not be mandatory for the execution of the long jump, while the results of the second experiment support the notion that erroneous auditory information negatively affects participants' visual behavior thereby impairing gait patterns and jumping performance. The modality appropriateness hypothesis (MAH) might offer an interesting explanation for these findings. It promotes the idea that perception within a multimodal setting will be dominated by the modality that is most appropriate (i.e., reliable) for task solution. If true, the long jump might be a motor task for which the visual modality appears to be the most reliable while the remaining modalities exert a lower sensory impact as illustrated within the first experiment of the second study. Concerning the second experiment, the negative effects of the delayed auditory feedback might result from impairing the most appropriate (i.e., visual) modality for the task of long jumping.

Based on these findings, a third study aimed to further scrutinize the premises of the MAH within a more controllable laboratory setting and an explicitly modality-appropriate task. If true that perception within a multimodal setting is dominated by the most appropriate (i.e., reliable) modality for task solution, it should be possible to reverse the effects of visual and auditory feedback depending on the requirements of the motor task. For rhythm reproduction tasks that require temporal (instead of spatial) precision, the auditory modality has been identified to be the most appropriate modality. To examine whether unimodal (i.e., auditory) stimulation is sufficient for successful rhythm reproduction or whether multimodal (i.e., audiovisual) stimulation might significantly add to task solution, participants were instructed to reproduce rhythmical patterns which were presented either visually, auditorily, or audiovisually. Results revealed that reproduction accuracy was highest in the presence of auditory information and lowest in the visual condition. Further, there were no differences between the auditory and the audiovisual stimulation indicating that the visual information did not add to task solution as suggested by the MAH. To summarize, the experimental series illustrated that, depending on certain task dimensions and demands, not all inputs from different sensory modalities equally contribute to perception and succeeding action in complex rhythmic motor tasks.

LIST OF PUBLICATIONS

This thesis is based on the following peer-reviewed articles:

STUDY 1

Hildebrandt, A., & Cañal-Bruland, R. (2020). Is gait-based visual regulation identical to gaze-based visual regulation in inexperienced athletes' long jump run-ups? *Human Movement Science*, *73*, 102681. https://doi.org/10.1016/j.humov.2020.102681

STUDY 2

Hildebrandt, A., & Cañal-Bruland, R. (2021). Effects of auditory feedback on gait behavior, gaze patterns and outcome performance in long jumping. *Human Movement Science*, 78, 102827. https://doi.org/10.1016/j.humov.2021.102827

STUDY 3

Hildebrandt, A., Grießbach, E., & Cañal-Bruland, R. (2022). Auditory perception dominates in motor rhythm reproduction. *Perception, 51,* 403-416. https://doi.org/10.1177/03010066221093604

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LIST OF ABBREVIATIONS

ANOVA	analysis of variance
AOI	area of interest
CE	constant error
CI	confidence interval
DAH	directed attention hypothesis
IRH	information reliability hypothesis
ISI	interstimulus interval
MAH	modality appropriateness hypothesis
MLE	maximum likelihood estimation
MPH	modality precision hypothesis
MSI	multisensory integration
SD	standard deviation
UA	unity assumption
VE	variable error

CHAPTER 1

INTRODUCTION

1 INTRODUCTION

In August 2021, German long jumper Malaika Mihambo won the gold medal in the dramatic final of the Olympic long jump competition in Tokyo. Although she admitted that she repeatedly struggled to find her *optimal run-up rhythm* throughout the competition[1] resulting in two invalid attempts (i.e., the foul line has been crossed), Mihambo eventually managed to outperform her direct opponents US American Brittney Reese and Nigerian athlete Ese Brume with a jumped distance of 7.00 m in her very last attempt.

To generate such an optimal rhythm for the coordination of the long jump run-up and, consequently, to leap as far as possible, a combination of both high run-up velocity and high precision to hit the take-off board properly seems to be of particular importance (Hay, 1986). More specifically, prior studies have demonstrated that athletes' jumped distance is closely intertwined with their run-up velocity immediately before the take-off (see e.g., Hay & Miller, 1985; Hay & Nohara, 1990). As trivial as this connection may seem at first sight, however, previous long jump events, for instance, at the Olympic Games or World Championships, have illustrated that even professional athletes commonly fail to optimally coordinate their run-up. In fact, 34% of all jumps in the men's and 31% of all jumps in the women's Olympic long jump final 2021 turned out to be invalid – probably due to a suboptimal rhythmic coordination of the run-up. While these statistics generally highlight the complex requirements of the long jump, they also give rise to the question of which factors underlie the successful execution of this complex rhythmic motor task.

In this regard, previous studies particularly emphasized the importance of visual input for the execution of motor precision tasks (cf. Howard & Templeton, 1966; Sinnett et al., 2007; Welch & Warren, 1986). In a similar vein, research on the topic of long jumping promoted the fundamental idea that visual input is used to guide and regulate an athlete's step behavior during the run-up. That is, a plethora

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[1] This statement was part of an online interview between Malaika Mihambo and journalist Johannes Holbein (SWR Sport) from December 2021: https://www.swr.de/sport/mehr-sport/leichtathletik/sportmoment-2021-weitspringerin-malaika-mihambo-oftersheim-gold-olympische-spiele-100.html

of seminal investigations (cf. Bradshaw & Aisbett, 2006; Hay & Koh, 1988; Lee et al., 1982) identified a universal pattern of increasing and systematically decreasing step variability across athletes' run-ups and concluded that athletes have visually regulated their strides to reduce movement variability.

While this decrease in athletes' step variability has been commonly proposed to describe visual regulation processes in long jumping (see e.g., Makaruk et al., 2015; Panteli et al., 2016; Theodorou & Skordilis, 2012), the contribution of other factors, such as auditory information, to the rhythmic-motor coordination of the long jump run-up has been hardly investigated to date. This is quite surprising given that MacPherson et al. (2009) suggested that rhythmical movement patterns may be particularly sensitive to auditory information. Consequently, there is reason to assume that auditory input might be crucial for the execution of the rhythmic long jump run-up as well. Additional anecdotal evidence for this assumption is provided by several long jumpers who demand a specific clapping rhythm from the audience to rhythmically synchronize their movements.

In sum, as the visual system has been characterized by a higher sensitivity in spatial tasks while the auditory system is assumed to be dominant within temporal tasks (see e.g., Aschersleben & Bertelson, 2003; Lukas et al., 2014; Näätänen & Winkler, 1999; O' Connor & Hermelin, 1972; Recanzone, 2003; Recanzone, 2009; Sandhu & Dyson, 2012; Shimojo & Shams, 2001; Spence & Squire, 2003; Welch & Warren, 1980; Welch et al., 1986), one might hypothesize that both visual and auditory information might be integrated for the optimal coordination of the long jump run-up due to the unique combination of spatial (i.e., precise hitting of the take-off board) as well as temporal demands (i.e., maintaining a rhythmic stride pattern).

Based on these assumptions, this publication-based thesis aspires to address this multisensory interplay in complex rhythmic motor tasks by empirically investigating the contributions of visual and auditory information to the rhythmic motor coordination of the long jump run-up. To this end, Chapter 2 will first provide a theoretical overview on the topic of multisensory integration in general including a definition of key aspects of multisensory integration (Chapter 2.1) and an introduction to commonly proposed factors that have been closely associated with multisensory integration (Chapter 2.2). Further, four of these factors will be discussed according to their potential relevance for the integration of audiovisual information in long jumping and the experimental implementation within our investigations. As perceptual biases have been commonly observed within multisensory, especially audiovisual, contexts (De Gelder & Bertelson, 2003), Chapter 2.3 will focus on the crossmodal interactions between visual and auditory information in terms of intersensory bias. Finally, Chapter 2.4 will provide a brief review of previous findings on visual and auditory contributions to the successful coordination of complex rhythmic motor tasks. In Chapter 3, the research questions and the work program for the experimental series of this thesis will be outlined. Chapters 4, 5, and 6 each comprise a peer-reviewed empirical investigation related to the topic of multisensory (i.e., audiovisual) integration in the context of complex rhythmic motor tasks.

As introduced previously, visual regulation processes during the long jump run-up have been commonly assessed by means of gait parameters instead of examining direct visual behavior. Hence, the first study (Chapter 4) aimed to scrutinize the importance of visual information for the long jump run-up by using portable eye-tracking technology to directly investigate athletes' gaze behavior. As auditory information might also affect the rhythmic motor coordination of the run-up, the second study (Chapter 5) extended the experimental paradigm of the first study by manipulating auditory feedback to analyze the impact of auditory information in the multisensory context of long jumping. Finally, a third study will be reported in Chapter 6 in which the findings of the previous investigations were re-evaluated within the more controllable and less constrained laboratory task of motor rhythm reproduction. Last but not least, all empirical results will be thoroughly reviewed and discussed from a theoretical and practical perspective in Chapter 7 before elaborating on some methodological challenges and further directions for future research.

CHAPTER 2

THEORETICAL FRAMEWORK

2 THEORETICAL FRAMEWORK

"More often than not, the judgments we think we are making based on information from a single sense, such as vision, are strongly influenced by seemingly irrelevant but informative cues from other senses such as hearing and touch. Sensory judgments are rarely exclusive to a single sense because multiple sensory channels converge on and share the use of the neural processes that mediate perception and action." (Stein et al., 2014, p. 520).

As illustrated by Stein and colleagues (2014), nearly every situation of our daily life is (un)consciously affected by a broad variety of sensory inputs from different modalities within our environment. From crossing a frequented street as a pedestrian to returning an opponent's serve in tennis - all these more or less complex situations require us to integrate information from our different senses to generate a veridical and unambiguous percept of the environment and to initiate adequate actions (Calvert et al., 1998). Accordingly, given that inputs from different sensory modalities mutually shape our perceptual experiences and actions in a variety of different contexts (Auvray & Spence, 2008; Calvert et al., 2004; Driver & Spence, 2000), there is reason to assume that the integration of multisensory information might be equally important for the execution of rhythmic motor tasks. In this regard, due to the specific demands of both spatial (i.e., hitting the take-off board) and temporal precision (i.e., maintaining a rhythmic stride pattern), one might hypothesize that the integration of visual and auditory information might be particularly relevant for the optimal rhythmic motor coordination of the long jump run-up (see Chapter 1).

To adequately investigate the integration of visual and auditory information as well as their respective contributions to the execution of the rhythmic motor task of long jumping, the following chapter will provide a theoretical introduction to the topic of multisensory integration (MSI). To start with, key aspects of MSI will be outlined before elaborating on some recently discussed factors which have been identified to modulate the magnitude of MSI and which might be particularly relevant for the audiovisual interplay in long jumping and the experimental implementation within our empirical studies. Further, as perceptual biases are commonly observed in multisensory contexts, especially between the visual and the auditory modality (cf. De Gelder & Bertelson, 2003), the topic of audiovisual intersensory bias as well as some commonly proposed explanations of this multisensory phenomenon will be addressed. Finally, the last section of this chapter will briefly outline some previous findings on the contributions of visual and auditory information to the coordination of complex rhythmic motor tasks.

2.1 Key aspects of multisensory integration

Concerning the long history of research on multisensory processes from the late 19th century to date, it is not surprising that the resulting body of literature came up with various definitions of MSI. All these definitions commonly provide the idea that MSI can be characterized as an interplay between different sensory qualities leading to a corporate sensory impression (Stein & Meredith, 1993; Stein & Stanford, 2008; Stein et al., 2014). As amended by Stein et al. (2009), the resulting sensory impression appears to be significantly different from its unisensory components.

When compared to unisensory perception (i.e., generating a perceptual impression based on one sensory modality only), MSI has been identified to reveal some relevant advantages for the orientation of behavior. As each sensory modality uniquely contributes to the perception of a certain event, the informational value, and quality of the percept appear to be elevated when different sensory signals are jointly integrated (Stein & Stanford, 2008; Stein et al., 2014) thereby increasing perceptual accuracy (Alais & Burr, 2004; Alais et al., 2010; Ernst & Banks, 2002; Shams et al., 2005) and decreasing response latency (Rowland et al., 2007). Taken together, MSI seems to be obligatory to extract the most important information from either redundant or complementary sensory inputs in a variety of different situations – be it in social interactions or sports contexts - and therefore appears to be an indispensable ability to successfully orient within the environment (Alais et al., 2010; Burr & Alais, 2006; Ernst & Bülthoff, 2004; Talsma et al., 2010).

2.2 Cognitive & structural modulation of multisensory integration

With respect to the aforementioned perceptual advantages related to the integration of multisensory information, previous research has identified cognitive as well as structural factors which are assumed to modulate the magnitude of MSI in general (Radeau & Bertelson, 1977; Welch & Warren, 1980; Welch, 1999). As illustrated in Figure 2-1, cognitive factors encompass properties that are mainly associated with observer processes, whereas structural factors include concrete properties of the sensory stimuli (Spence, 2007; Stein & Stanford, 2008; Stein et al., 2014). According to Stein and Stanford (2008), these cognitive and structural factors are closely intertwined and mutually affect the manifestation of MSI.

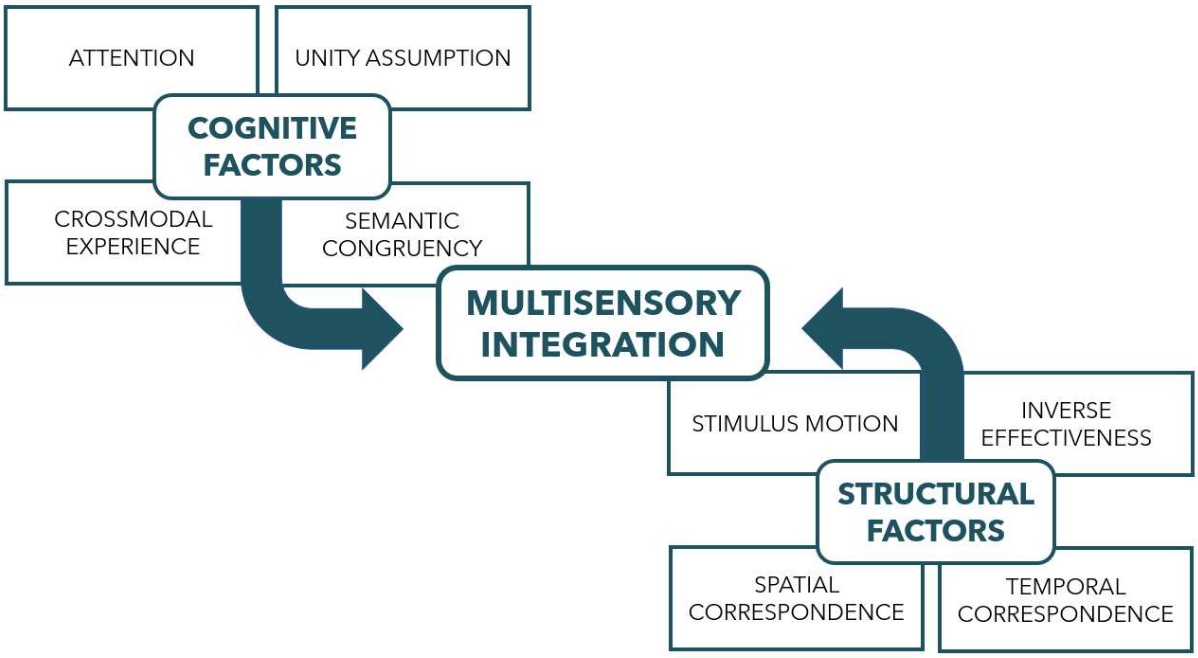

Figure 2-1. A schematic overview of cognitive as well as structural factors which have been identified to modulate the magnitude of MSI, conceptualized after Spence (2007), Stein and Stanford (2008), and Stein et al. (2014).

Since these factors have been thoroughly characterized and discussed within the seminal articles by Spence (2007), Stein and Stanford (2008) as well as Stein et al. (2014), the following sections will be dedicated to four of those factors which might be particularly relevant for i) the integration of visual and auditory input in the complex rhythmic motor task of long jumping due to its specific requirements and ii) the design of appropriate experimental paradigms to validate the initial assumptions of this thesis.

First, the cognitive factor of *crossmodal experience* (Chapter 2.2.1) appears to be essential for audiovisual integration in the setting of long jumping. That is, especially when considered synonymously with perceptual expertise (see Mann et al., 2007), crossmodal experience as the ability to extract relevant information from the environment and to integrate different sensory inputs for the selection of adequate actions within a given task seems to be fundamental to successful performance (Marteniuk, 1976). Further, as it can be assumed that the task-specific association between visual and auditory information in long jumping is obtained through repeated exposure to a given pattern of multisensory stimuli (i.e., training; see Williams et al., 2011), an investigation of audiovisual integration in long jumping might require an adequate level of participants' crossmodal experience.

Second, the structural factor of *temporal correspondence* (Chapter 2.2.2) between sensory inputs might play an important role in long jumping as well. That is, temporally aligned visual and auditory inputs (e.g., seeing one's own steps while hearing the corresponding step sounds) have been identified to facilitate audiovisual integration (see e.g., Bolognini et al., 2005, 2010) whereas temporally disconnected visual and auditory stimuli do not only impair the integration process (see e.g., Kadunce et al., 2001) but also motor performance (see e.g., Kennel et al., 2015).

Third, in direct relation to the factor of temporal correspondence (see e.g., Vatakis & Spence, 2007), it might also be particularly important for the optimal integration of visual and auditory information in the context of long jumping that these sensory inputs are assumed to have a common cause as described by the cognitive factor *unity assumption* (Chapter 2.2.3). In terms of the long jump, assuming unity between different sensory stimuli might indicate that, for instance, the sound of step sounds is actually attributed to one's own steps.

Finally, Williams et al. (1999) highlighted the importance of *attention* (Chapter 2.2.4) for the integration of multisensory inputs and optimal motor performance. Therefore, the appropriate alignment of attentional resources on task-relevant visual and auditory cues and the corresponding intake of significant information might also account for the optimal coordination of the long jump run-up.

2.2.1 Crossmodal experience

First of all, the development of humans' ability to integrate multisensory inputs is crucially related to (and depending on) the cognitive factor of crossmodal experience throughout the lifespan and therefore appears not to be innate in nature (Stein et al., 2014). By means of exposure to different combinations of various sensory inputs, the perceptual system will undergo a calibration process (Stein et al., 2014) thereby establishing associative networks and gaining crossmodal experience (Spence, 2007). Accordingly, the association cortex, an area of the cerebral cortex associated with the processing of various sensory information (Armstrong, 2021), appears to be of special importance for this process (Stein et al., 2014) as it is involved in the allocation of attention and consecutive behavior (Arnsten, 2009).

Previous research typically made use of various sensory manipulations to examine the impact of early crossmodal experience on the development of MSI in animals such as visual deprivation (e.g., Rauschecker, 1995; Wiesel & Hubel, 1963), auditory masking (e.g., Chang & Merzenich, 2003; Efrati & Gutfreund, 2011), providing random sensory cues (e.g., Xu et al., 2012) or providing unusual sensory input (e.g., Wallace & Stein, 2007). In sum, these manipulated early crossmodal experiences led to dramatical changes within the neurophysiological topographies associated with MSI (for an overview, see Stein et al., 2014) and hence provide support for the outstanding importance of appropriate crossmodal experience to develop proper MSI abilities.

Studies in animals (e.g., Barraclough et al., 2005; Romanski, 2007) as well as in humans (e.g., Baier et al., 2006; Beauchamp et al. 2004; De Gelder & Bertelson, 2003; King & Calvert, 2001) suggest that different crossmodal experiences modulate the structure of the association cortex which is crucially involved in multisensory processing. However, the aforementioned studies also revealed that the perceptual system is able to recalibrate in response to altered crossmodal experiences, for instance, due to the loss of sight or hearing (Bertelson, 1998; De Gelder & Bertelson, 2003; Harris, 1965; Held, 1965). As stated by Stein et al. (2014), this recalibration process gives rise to the existence of multisensory plasticity indicating that different sensory qualities can compensate for each other in terms of both short-term and long-term sensory deprivation (Fortin et al., 2008; Goyal et al., 2006; Kujala et al., 1995; Merabet et al., 2008; Rice, 1970; Röder et al., 1999; Wanet-Defalque et al., 1988). Thus, even the lack of essential crossmodal experiences in early life can be balanced by appropriate sensory impressions in later stages of life to a certain extent with some detriments in efficacy. Considering the reorganizational abilities of the cortex, Ghazanfar and Schroeder (2006) even go so far as to claim that it might be multisensory in nature.

2.2.2 Temporal correspondence

Stein et al. (2014) claimed that the repeated exposure to temporally correspondent stimuli is mandatory for the development of crossmodal experience within a given setting. As a matter of fact, temporal correspondence between different sensory inputs, also described as the *temporal rule,* represents a quite intuitive yet crucial modulating factor for MSI. That is, stimuli from different sensory modalities that are closely aligned in time are assumed to facilitate MSI in general (Meredith et al., 1987; Recanzone, 2003) and audiovisual integration in particular (Bermant & Welch, 1976; Bolognini et al, 2005, 2010; Frassinetti et al., 2002; Jack & Thurlow, 1973; Jones & Jarick, 2006; Lu et al., 2009; Radeau & Bertelson, 1977; Radeau & Bertelson, 1987). According to Stein et al. (2014), the facilitating effect of temporal correspondence for MSI is based on a general response enhancement of multisensory neurons by temporally aligned stimuli whereas temporally unrelated sensory inputs often inhibit proper integration (Kadunce et al., 2001; Meredith et al., 1987; Stein & Meredith, 1993). Intriguingly, the importance of temporal correspondence between different sensory inputs seems to be independent of any task-relevance of stimuli from different sensory origins. For instance, the response time within a visual search paradigm can be distinctly reduced by the synchronous presentation of an auditory but somewhat task-irrelevant auditory cue (Alais et al., 2010; Calvert & Thesen, 2004). Similarly, participants' performance within an auditory detection task can be drastically enhanced by synchronous task-irrelevant visual cues (Lovelace et al., 2003). As inferred by Stein et al. (2014), these positive effects of task-irrelevant stimuli are based on an increase in sensitivity to the sensory event and a concomitant reduction of perceptual uncertainty.

Temporal correspondence does not necessarily require that different sensory inputs need to occur at exactly the same time but rather implies temporal proximity (King & Palmer, 1985; Meredith et al., 1987; Welch & Warren, 1980). That is, there is also evidence that MSI can still be facilitated when different sensory inputs are presented with a slight temporal delay (see McDonald et al., 2000). In fact, there is a quite broad time window for temporal MSI (Meredith et al., 1987; McDonald et al., 2001) which can cover several hundred milliseconds (Stein & Stanford, 2008). However, if the temporal delay between different sensory inputs is too long, the integration process can be severely impaired (see e.g., Kadunce et al., 2001) resulting in a deterioration of motor performance (see e.g., Kennel et al., 2015).

2.2.3 Unity assumption

In close relation to the structural factor of temporal correspondence (Radeau & Bertelson, 1977; Warren et al., 1981; Vatakis & Spence, 2007), an observer's unity assumption, i.e., the subjective phenomenon of (un)consciously attributing different sensory inputs to the same event, has also been identified to affect the manifestation of MSI (Talsma et al., 2010; Welch & Warren, 1980; Welch, 1999). In general, observers are more likely to experience unity (and assume a common spatiotemporal cause) between different sensory inputs which appear to be congruent and somewhat connected (Bedford, 2001; Spence, 2007). As reported by Welch and Warren (1980), the perception of different sensory inputs as a single multisensory event or as multiple separate unimodal events is a result of the interplay between different variables, for instance, structural compliance between stimuli (Radeau & Bertelson,1987), observer's experience with specific stimulus pairings (Jackson, 1953), experimental instructions (Arnold et al., 2005; Warren et al., 1981; Welch & Warren, 1980) and stimulus consistency or compellingness (i.e., the stimulative nature of a stimulus, see Warren et al., 1981; Welch & Warren, 1980).

2.2.4 Attention

Finally, MSI is inevitably subjected to attention as different sensory inputs from the environment compete for attentional resources (Stein & Stanford, 2008; Talsma et al., 2010). That is, these available inputs are selected for further processing with respect to their informational value and their perceptual relevance through the alignment of attention while attended stimuli benefit from more efficient processing when compared to relatively unattended stimuli (Alais et al., 2010). Concerning the aforementioned competition between inputs from different sensory modalities, attention can manifest itself in two different modes. In case multiple stimuli compete for attentional resources (i.e., individual stimulus salience is low), attentional alignment is operating in a *top-down* fashion to properly organize (and facilitate) multisensory processing (Alsius et al., 2005; Alsius et al., 2007; Mishra et al., 2010; Soto-Faraco & Alsius, 2007; Talsma et al., 2007; Van Ee et al., 2009). In this regard, explicit instructions, for example on attentional orientation, can substantially guide top-down attentional alignment (Vatakis & Spence, 2007; Welch & Warren, 1980; Welch, 1999). In contrast, when competition between stimuli is low (i.e., individual stimulus salience is high), attention can be captured in a stimulus-driven (i.e., *bottom-up*) manner in which multisensory stimuli will be selected for attentional processing more or less automatically (Van der Burg et al., 2008).

2.3 Crossmodal interactions between vision and audition

2.3.1 The perceptual phenomenon of intersensory bias

Perceiving different, (temporally) correspondent, sensory inputs as belonging to the same event (cf. UA, Welch & Warren, 1980; see Chapters 2.2.2 and 2.2.3) does not necessarily imply that these inputs contribute to perception (and succeeding action) to an equal extent. That is, as the perceptual system is required to deal with the unique characteristics, specifics, and complexities of each modality while attempting to integrate multiple stimuli into a convenient percept (Stein & Stanford, 2008), these different sensory inputs actually appear to be evaluated and weighted based on their informational value for a certain event through the alignment of attention (see Chapter 2.2.4; Alais et al., 2010; Burr & Alais, 2006; Ernst & Banks, 2002; Shams et al., 2005).

In this regard, previous research has shown that different sensory inputs interact with each other and mutually affect their stimulus manifestations (see e.g., Alais et al., 2010; Sekuler et al., 1997; Shimojo & Shams, 2001). Beyond, Sanabria et al. (2007) reported that a stimulus in one sensory modality cannot only modulate the perceived intensity of a simultaneously presented second stimulus in another modality but also dominate an observer's perception in a multimodal context. This phenomenon is referred to as *intersensory bias* (Lukas et al., 2014; Welch & Warren, 1980) and is hypothesized to emerge as an attempt of the perceptual system to generate the most veridical percept for task solution in both discrepant and nondiscrepant task settings (Welch & Warren, 1980). In addition, Freides (1974), as well as O'Connor and Hermelin (1972), suggested that the occurrence of intersensory bias demonstrates that some modalities might be more eligible for certain task dimensions than others. According to De Gelder and Bertelson (2003), it is therefore not surprising that perceptual biases and corresponding effects of modality dominance are very likely to occur in multisensory task contexts. Hence, due to the specific task dimensions of the long jump run-up (i.e., spatial as well as temporal demands), the issue of intersensory bias between visual and auditory input needs to be considered in the setting of complex rhythmic motor tasks as well.

2.3.2 Intersensory bias between vision and audition

With respect to the sensory modalities of vision and audition which might be particularly relevant for the optimal coordination of the long jump run-up and the empirical endeavor of this thesis, a review of the existing literature on multisensory processes first and foremost revealed an outstanding bias of the visual modality over the auditory modality (cf. Hutmacher, 2019; Shimojo & Shams, 2001).

An early and reliably replicable demonstration of visual dominance over the auditory input has been introduced by Colavita (1974). Within an experimental paradigm in which participants are required to make speeded and accurate decisions in reaction to visual (e.g., left keypress), auditory (e.g., right keypress), or audiovisual (e.g., left and right keypress) stimulus streams, the *Colavita effect* per se reflects participants' tendency to miss out on auditory input during audiovisual stimulation. According to Spence et al. (2012), it appears as if the simultaneous presentation of the visual stream impaired participants' perception of and hindered their reaction to the auditory input.

In a similar vein, Welch and Warren (1980), as well as Bertelson and De Gelder (2004), inferred that auditory stimuli are commonly assumed to emanate from the spatial location of temporally correspondent visual stimuli. That is, for instance, skilled ventriloquists manage to create the impression of a talking puppet as their voices are attributed to the moving mouth of the puppet. This effect of *spatial ventriloquism* (see also Choe et al., 1975; Spence, 2007) represents another intriguing example of visual dominance over the auditory modality in terms of stimulus localization (cf. Alais & Burr, 2004; Howard & Templeton, 1966; Lukas et al., 2014; Stratton, 1897). Interestingly, the magnitude of spatial ventriloquism is expected to be higher when audiovisual stimuli are closely aligned in time. (Bermant & Welch, 1976; Hairston et al., 2003; Jack & Thurlow, 1973; Jackson, 1953; Radeau & Bertelson, 1977; Slutsky & Recanzone, 2001). Additionally, visual input has also been identified to dominate speech perception (McGurk & MacDonald, 1976).

Despite the profound evidence of visual dominance over the auditory modality, the results of more recent studies promote the idea that the visual modality can be dominated and modulated by the auditory modality, too. For instance, when participants were required to judge interval durations and stimulus frequencies, auditory stimuli clearly outperformed visual input (Burr et al., 2009; Gebhard & Mowbray, 1959; Recanzone, 2003; Shipley, 1964; Wada et al., 2003; Welch et al., 1986). Additionally, simultaneous auditory stimuli have been shown to affect the perceived duration of visual signals (Walker & Scott, 1981), the perceived intensity of a stimulus (Stein et al., 1996), and manual interception (Tolentino-Castro et al., 2022). Interestingly, there are also a plethora of studies arguing in favor of a *temporal ventriloquism* effect indicating that the perceived timing of visual stimuli can be modulated by auditory input (cf. Aschersleben & Bertelson, 2003; Fendrich & Corballis, 2001; Parise & Spence, 2008; Shams et al., 2000;

Vroomen & Keetels, 2006). In this regard, Morein-Zamir et al. (2003) reported that task-irrelevant sound signals can significantly affect participants' judgment of the moment of occurrence of visual targets. Finally, the visual temporal resolution (Shimojo et al., 2001), as well as perceptual interpretation of a visual stimulus, can be altered by auditory input (cf. Sekuler et al., 1997; Zampini & Spence, 2004).

In sum, the initial hypothesis by Freides (1974), as well as O'Connor and Hermelin (1972), proved to be true as the visual and the auditory modality appear to be particularly specialized for certain tasks. Concerning the previous findings on crossmodal interactions between vision and audition, research has come to the conclusion that the visual system is characterized by a higher accuracy in tasks that require a spatial decision while the auditory system is assumed to be more sensitive within tasks that involve temporal judgments (see e.g., Aschersleben & Bertelson, 2003; Lukas et al., 2014; Näätänen & Winkler, 1999; O'Connor & Hermelin, 1972; Recanzone, 2003; Recanzone, 2009; Sandhu & Dyson, 2012; Shimojo & Shams, 2001; Spence & Squire, 2003; Welch & Warren, 1980; Welch et al., 1986; Chapter 1). Accordingly, potential interactions between visual and auditory input with respect to the rhythmic motor coordination of the long jump run-up should be taken into account.

2.3.3 Explanations of intersensory bias

After characterizing the perceptual phenomenon of intersensory bias with special emphasis on the crossmodal interactions between visual and auditory information, the following section will now elaborate on some commonly suggested approaches to explain the emergence of intersensory bias. In this regard, Welch and Warren (1980) proposed a conceptual model (see Figure 2-2 for an adapted version of the model) indicating that intersensory bias might be the result of a causal chain that mainly comprises three dimensions of modulating factors (cf. Chapter 2.2).

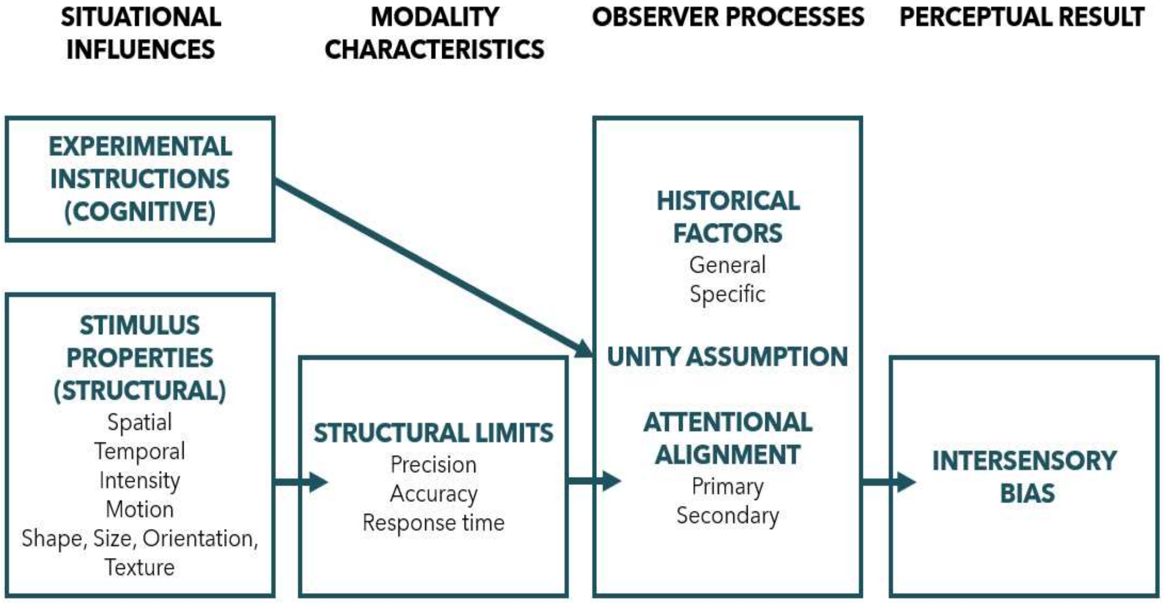

Figure 2-2. An adapted model of intersensory bias, originally conceptualized by Welch and Warren (1980).

To start with, *situational influences* basically represent the discrimination between cognitive and structural factors which have been identified to affect the manifestation of MSI in general (see Chapter 2.2; Spence, 2007; Stein & Stanford, 2008; Stein et al., 2014). While experimental instructions (e.g., on the allocation of attention) are directly associated with the dimension of observer processes, stimulus properties comprise structural features of the sensory input (e.g., temporal correspondence, see Chapter 2.2.2) which in turn correspond with the dimension of *modality characteristics*. As the different sensory modalities are each characterized by specific qualities, for instance in terms of spatial or temporal precision and accuracy (see Chapter 2.3.2), this dimension considers that the information pick-up within a certain situation is structurally affected by basal and biologically determined modality characteristics such as receptor properties and nerve conduction. In direct connection to the dimensions of situational influences and modality characteristics, Welch and Warren (1980) have identified *observer processes,* such as an observer's crossmodal experience with certain stimulus configurations (see Chapter 2.2.1), to be a significant determinant of intersensory bias. In this regard, the authors differentiate between general and specific historical factors which shape an observer's individual crossmodal experience.

While general historical factors describe an observer's general experience with the joint occurrence of certain modalities from previous situations (i.e., common history of the modalities), specific historical factors determine an observer's experience with a certain stimulus combination and the resulting manifestation of the UA (see Chapter 2.2.3). More specifically, Welch and Warren (1980) claim that the strength of an observer's UA is crucially intertwined with the occurrence of intersensory bias as it is more likely to occur when unity between stimuli is assumed to be high. Finally, Welch and Warren (1980) report that an observer's attentional alignment can also substantially affect the manifestation of intersensory bias (cf. Chapter 2.2.4). In this regard, the authors distinguish between primary attention and secondary attention. Primary attention characterizes a modality's general ability to attract attention due to its specific characteristics (i.e., general salience, previous experiences) whereas secondary attention describes a more artificial alignment of attention due to experimental instructions, recent experience, or task demands.

Apart from the model by Welch and Warren (1980), previous research has commonly proposed three theoretical approaches to explain the phenomenon of intersensory bias - or the dominance effects of vision in spatial tasks and audition in temporal tasks respectively – which mainly relate to the model dimensions of modality characteristics and consecutive observer processes. These theoretical approaches as well as an additional statistical perspective on intersensory bias will be introduced in the remainder of this Chapter.

The first explanatory approach to intersensory bias, the *modality precision hypothesis* (MPH, Choe et al., 1975; Fisher, 1968; Howard & Templeton, 1966; Kaufman, 1974) claims that in a discrepant setting (i.e., in case of discrepant sensory inputs from different modalities), the perceptual system will favor input from the sensory modality which is perceived to offer the most precise resolution of a certain event. According to Welch (1999), observers correspondingly attribute their attentional resources to the most precise sensory modality. That is, for instance, while vision has been demonstrated to provide a more precise spatial resolution, the MPH would expect a greater intersensory bias towards the visual modality in situations that require a spatial decision. Early evidence for this assumption was provided by Jack and Thurlow (1973) as their experiment revealed a more distinct bias of vision over audition when spatial localization was required within the vertical dimension than compared to the horizontal dimension. According to the authors, this finding resembles the less precise auditory localization in the vertical dimension and the resulting higher vulnerability to being biased by vision. Otherwise, however, research on the MPH revealed ambivalent results (cf. Fishkin et al., 1975; Welch & Warren, 1980).

As discussed previously in section 2.2.4 and in terms of the model of intersensory bias by Welch and Warren (1980), attention is considered an important modulating factor for both MSI in general and intersensory bias in specific. According to the second explanatory approach for intersensory bias, the *directed attention hypothesis* (DAH)*,* intersensory bias might occur due to a differential alignment of attention between different sensory inputs with the result that perception is substantially dominated by the attended modality. In this regard, Shams et al. (2000) suggest that the modality with higher discontinuity (i.e., higher salience) will attract an observer’s attention and becomes more important for task solution (see also Andersen et al. 2005; Shimojo & Shams, 2001). Posner et al. (1976), however, argued that there seems to be a general intermodal difference in terms of salience or capability to capture attention leading to an individual predisposition for the observer (cf. primary attention, Welch & Warren, 1980). In terms of the evident dominance of the visual modality, Posner et al. (1976) claim that an observer’s primary attention to vision is not per se more pronounced. In fact, visual warning signals are less salient and therefore less attention-attracting than, for instance, auditory warning signals. However, Posner et al. (1976) propose that this lack of salience within the visual modality biases observers to primarily direct attention toward visual stimuli. Evidence for this hypothesis was provided within pioneering investigations by Canon (1970) and Colavita and Weisberg (1979). More recently, Andersen et al. (2004, 2005) reported that the alignment of secondary attention (e.g., by experimental instructions) can substantially affect the response patterns for different modalities.

The *modality appropriateness hypothesis* (MAH) offers a commonly proposed explanation and a "rule of thumb" (Alais et al., 2010) for intersensory bias which unifies some key aspects of the MPH and the DAH. In general, the MAH is based on the notion that the sensory modalities, although each capable of various functions, are particularly specified to process information within appropriate dimensions (Freides, 1974; Lukas et al., 2010, 2014; O'Connor & Hermelin, 1972). In particular, MAH is advocating the fundamental idea that a multimodal task setting will be dominated by the most appropriate (i.e., accurate, sensitive, or reliable) modality (Andersen et al., 2005; Matuz et al., 2019; Shimojo & Shams, 2001; Talsma et al., 2010; Wada et al., 2003; Welch & Warren, 1980; Welch, 1999). [2]

Similar to the DAH, attention also appears to be of particular importance regarding the premises of the MAH. That is, the appropriateness of a certain sensory modality is closely related to an observer's attentional alignment (cf. Lukas et al., 2010; Welch, 1999). According to Andersen et al. (2005) as well as Welch and Warren (1980), the human perceptual system can purposefully distribute attentional resources based on the relative reliability (i.e., appropriateness) of sensory inputs. Welch (1999) stated that more attentional resources are attributed to the appropriate modality in a multimodal task setting. Following the more rigorous interpretation by Hass et al. (2012), the MAH would even predict that the most appropriate modality only might contribute to perception while less appropriate modalities are neglected. To summarize, the alignment of attention and, consequently, the processing of different sensory inputs due to the level of appropriateness are depending on stimulus properties (i.e., temporal, or spatial character, intensity, movement, salience, shape, size, orientation, texture; Shimojo & Shams, 2001; Welch & Warren, 1980; Figure 2-2) and task demands (e.g., whether it requires spatial or temporal processing; Lukas et al., 2014). Concerning

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[2] Please note that a very similar approach has been introduced as the *information reliability hypothesis* (IRH, cf. Andersen et al., 2005; Schwartz et al., 1998) which proceeds to assume that perception will be dominated by the modality that provides the most reliable information within a certain task setting. However, as the premises of the MAH and the IRH are almost identical, this thesis will exclusively focus on the MAH.

the latter, Welch and Warren (1980) reported that the appropriateness of a certain modality will be more pronounced within (temporally or spatially) more complex tasks thereby mirroring previous findings on visual and auditory bias effects (see Chapter 2.3.2).

Interestingly, the MAH is well compatible with the approach of *maximum likelihood estimation* (MLE, also referred to as the optimal integration hypothesis, e.g., Ernst & Banks, 2002) which considers intersensory bias from a statistical perspective. Enrooted in the Bayesian probability theory (e.g., Körding & Wolpert, 2004; see also Chapter 6), the method of MLE can be considered a statistical formalization of the MAH (Alais et al., 2010). That is, according to MLE, different sensory inputs are automatically weighted with respect to their informational value and reliability (cf. Helbig & Ernst, 2008; see also Chapters 2.3.1 and 2.3.2) to attain the statistically optimal (i.e., most reliable, and least variable) percept of a given situation. Hence, human perception is assumed to be less driven by less reliable sensory inputs resulting in a bias towards the more reliable modality respectively (Alais & Burr, 2004; Ernst & Banks, 2002; Ernst & Bülthoff, 2004). However, in contrast to the rigid interpretation of the MAH (cf. Hass et al., 2012) and according to the view that modality dominance is never absolute (Rock & Victor, 1964), less reliable sensory input is never fully neglected but simply down-weighted in MLE (Alais et al., 2010).

2.4 Contributions of visual and auditory information to the execution of complex rhythmic motor tasks

After providing a theoretical overview of multisensory integration and elaborating on related constructs within the previous sections, this final chapter within the theoretical framework of the current thesis will now briefly review the current state of research concerning visual and auditory contributions to the rhythmic motor coordination of the long jump to clarify our empirical endeavor. A more detailed discussion of relevant studies is provided in the respective sections of our empirical studies (Chapters 4.1 and 5.1).

As postulated within the previous section on the topic of intersensory bias, there is a robust bias of the visual modality over the auditory modality within a variety of different settings, however, not only in terms of a perceptual dominance but also as concerns the outstanding number of studies on the visual modality (Hutmacher, 2019). This bias also seems to be present concerning research on complex rhythmic motor tasks in general, and the long jump in specific. That is, previous research in the setting of long jumping provided evidence that visual input might be particularly important for the rhythmic-motor coordination of the long jump run-up (see Chapter 1). In this regard, Lee et al. (1982) analyzed participants' gait patterns during the long jump run-up and identified a systematic pattern of increasing variability (i.e., standard error) in toe-board distances followed by a distinct decrease in variability. According to Lee et al. (1982), this decrease in variability can be considered indicative of visual regulation processes taking part during the run-up. Further, the authors inferred that the long jump run-up appears to be two-phased with an acceleration phase and a zeroing-in phase while the moment of highest variability in toe-board distance marks the transition between both phases and the initiation of visual regulation.

Similarly, Hay and Koh (1988) advocated the idea that the temporal course of toe-board variability represents visual regulation processes, however, defining variability by means of the standard deviation. Since then, the maximum standard deviation of toe-board distance became the golden standard to determine visual regulation processes during the long jump run-up by means of gait behavior (see also Berg et al., 1994; Bradshaw & Aisbett, 2006; Hay, 1988; Makaruk et al., 2015; Panteli et al., 2014, 2016; Scott et al., 1997; Theodorou et al., 2011; Theodorou & Skordilis, 2012). Moreover, according to Bradshaw and Aisbett (2006), this factor of *gait-based visual regulation* is directly associated with jumped distance as an earlier initiation of gait-based visual regulation led to farther jumps. To conclude, previous research in the setting of long jumping indicated that athletes' gait behavior, as well as their jumped distance, might substantially depend on visual regulation processes during the run-up.

On the contrary, the impact of other sensory information such as auditory feedback on the rhythmic motor coordination of the long jump has been neglected to date. Given that MacPherson et al. (2009) hypothesized that temporally challenging rhythmical tasks (such as the long jump) might be specifically sensitive to auditory information, it is quite surprising that the effects of auditory feedback on the rhythmic motor coordination of the long jump have not been investigated to date. Additionally, bearing in mind that the visual system is assumed to be dominant in spatial tasks, while the auditory system is assumed to be dominant within temporal tasks (see e.g., Aschersleben & Bertelson, 2003; Lukas et al., 2014; Näätänen & Winkler, 1999; O' Connor & Hermelin, 1972; Recanzone, 2003; Recanzone, 2009; Sandhu & Dyson, 2012; Shimojo & Shams, 2001; Spence & Squire, 2003; Welch & Warren, 1980; Welch et al., 1986), the long jump with its unique combination of spatial (i.e., precise hitting of the take-off board) *and* temporal (i.e., maintaining a rhythmical stride pattern) demands might not only attract the visual but also the auditory modality.

In fact, recent reviews by Schaffert et al. (2019), as well as Stanton and Spence (2020), highlighted the importance of concurrent auditory feedback (e.g., the sound emanating from racquet-ball contact in tennis, Cañal-Bruland et al., 2018) for the execution of (complex) motor tasks. Similarly, Agostini et al. (2004) demonstrated that motor performance in hammer throwing (i.e., larger throwing distances), as well as task execution (i.e., more standardized movement pattern with less variability across trials), can be improved through action-induced rhythmic sounds (i.e., the sound produced by the contact between hammer and air) associated to their best personal throw.

In contrast, absent auditory feedback has been shown to deteriorate motor performance. For instance, a recent study by Schaffert et al. (2020) revealed that movement precision in rowing decreased under conditions of absent auditory feedback (i.e., auditory deprivation) thereby corroborating the findings of an earlier study by Takeuchi (1993) who showed that the match performance of experienced tennis players decreased under auditory deprivation. Beyond, Kennel et al. (2015) illustrated that delayed auditory feedback significantly affected movement performance movement stability in the complex rhythmic task of hurdle jumping. Hence, concerning these results, one might assume that auditory input might also be crucial to motor performance in complex tasks as auditory feedback seems to comprise relevant information about temporal aspects of movement and may serve the purpose of error correction during performance.

To conclude, research on the complex rhythmic motor task of long jumping has identified a gait-based parameter (i.e., the maximum standard deviation of toe-board distance) which is assumed to indicate a reduction in step variability based on visual regulation processes (cf. Hay & Koh, 1988). Since then, this parameter of gait-based visual regulation has been commonly proposed in long jump research. On the contrary, although recent studies emphasized the importance of auditory information for the execution of complex motor tasks and corresponding motor control, the effects of auditory feedback on the rhythmic coordination of the run-up as well as the respective multisensory interplay between vision and audition have not been examined so far.

CHAPTER 3

RESEARCH QUESTIONS & WORK PROGRAM

3 RESEARCH QUESTIONS & WORK PROGRAM

As illustrated within Chapters 1 and 2 of this thesis, the integration of both visual and auditory information might be particularly relevant for the successful coordination of the complex rhythmic motor task of long jumping. However, the question of whether and how audiovisual information affects the execution of the long jump has hardly been investigated so far. For this reason, a series of three empirical studies (see Figure 3-1) has been composed based on the initial theoretical deliberations (see Chapters 2.2 to 2.4) to further scrutinize the role of audiovisual integration in complex rhythmic motor tasks by the example of long jumping.

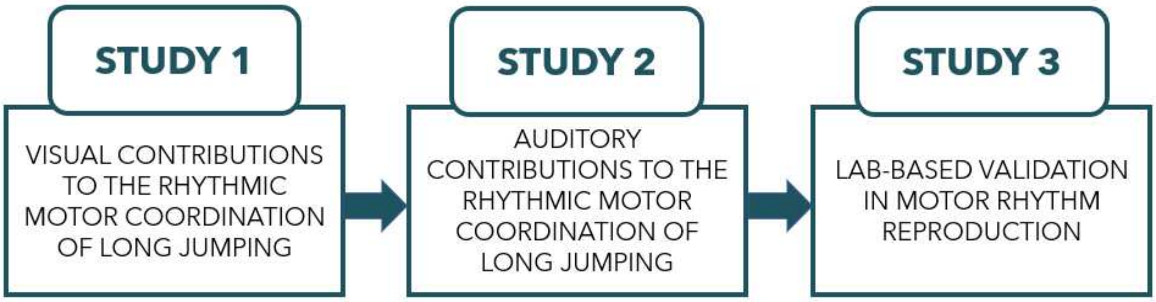

Figure 3-1. Research trajectory for the experimental series of this thesis.

In general, the empirical section of this thesis encompasses two field-based studies in long jumping (Chapters 4 and 5) as well as a final laboratory study on motor rhythm reproduction (Chapter 6) to address the following research questions:

First, as visual regulation processes during the long jump have only been examined indirectly to date (see Chapter 2.4), the first empirical study of this thesis aimed to apply a more direct approach to the long jump run-up and to validate the commonly proposed parameter of gait-based regulation by means of actual visual behavior. As suggested by Abernethy et al. (2001), the location and temporal distribution of a person's gaze might reveal interesting aspects of information pick-up strategies (see also Abernethy & Russell, 1987; Goulet et al. 1989). For this reason, the technology of mobile eye-tracking has been implemented into the experimental paradigm to directly investigate participants' gaze behavior during the long jump run-up and examine the importance of the visual modality for long jumping performance first (i.e., gait behavior and jumped distance; cf. Bradshaw & Aisbett, 2006). These objectives lead to the following research question:

1) Is there a gaze-based equivalent to the gait-based visual regulation parameter of the maximum standard deviation of toe-board distance? (Chapter 4)

Second, based on i) the deliberations by MacPherson et al. (2009), ii) the findings of recent studies on the impact of auditory feedback on motor performance (see e.g., Schaffert et al., 2020; Chapter 2.4) and iii) the specific rhythmic temporal demands of the task itself (cf. Recanzone, 2003), there is reason to assume that input from the auditory modality might be crucial for the optimal coordination of the long jump run-up, too. Therefore, the experimental design of Study 1 has been extended in Study 2 by implementing two auditory manipulations, i.e., auditory deprivation (see Schaffert et al., 2020) and delayed auditory feedback (see Kennel et al., 2015) to the paradigm to validate the initial assumptions thereby addressing the following research question:

2) Does (manipulated) auditory feedback affect participants' gait, gaze, and outcome performance in long jumping? (Chapter 5)

Third, given the unexpected results of the second study in terms of the auditory deprivation (see first experiment in Chapter 5), a third study was conducted to validate the findings of the previous investigation within a more simplified, laboratory paradigm. As the auditory deprivation in Study 2 did not show any negative effects on participants' gait and gaze patterns or jumped distances (i.e., that visual information only was sufficient for successful task coordination), we hypothesized that the long jump might be a visually dominated task in keeping with the MAH (see Chapter 2.3.3) and that participants did not benefit more from multimodal stimulation (i.e., visual and auditory input provided) than from unimodal stimulation (i.e., visual input only). To further scrutinize these unpredicted effects of modality appropriateness in the long jump setting, we decided to run a final lab-based investigation in which we could control for the appropriateness of a given task. As we assumed that the findings from the second study should replicate within an *auditorily* dominated task setting as well, we opted for a simplified, rhythmic motor task for which the most appropriate modality has been known in advance. Ultimately, as it has been identified to be favorably solved within the auditory modality (cf. Chen et al., 2002; Gault & Goodfellow, 1938; Glenberg & Jona, 1991; Hove et al., 2013; Kolers & Brewster, 1985; Patel et al., 2005; Repp & Penel, 2004), we decided to use the task of motor rhythm reproduction to investigate the following research question:

3) *Does only the most appropriate modality (i.e., audition) add to successful rhythm reproduction in a multimodal context?* (Chapter 6)

CHAPTER 4

VISUAL REGULATION IN LONG JUMPING

4 STUDY 1: IS GAIT-BASED VISUAL REGULATION IDENTICAL TO GAZE-BASED VISUAL REGULATION IN INEXPERIENCED ATHLETES' LONG JUMP RUN-UPS?

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Abstract

In long jumping, athletes need to hit a take-off board with both high precision and high run-up velocity to leap as far as possible. It is commonly agreed that visual regulation plays a crucial role in long jumping. To identify visual regulation, researchers have typically relied on analyses of variability in step parameters (i.e., "gait-based visual regulation"). The aim of the current study was to examine whether gait-based visual regulation coincides with measures of actual gaze control, referred to as "gaze-based visual regulation". Therefore, 15 participants performed long jumps and run-throughs while wearing a mobile eye-tracker. To compare gait-based with gaze-based visual regulation, a digital camera recorded all trials for subsequent frame-by-frame analyses of step parameters. Results revealed that gait-based visual regulation coincided with the step of the longest gaze (i.e., dwell time) on the take-off board but not with the step of initial gaze on take-off board. This finding supports the notion of visuomotor control of motor variability by means of longer gazing periods at the take-off board. In addition, our results provide initial insights to coaches and athletes on the particular requirements of visual regulation and the relationship between gait and gaze in the long jump approach.

Keywords: Gait; Gaze; Visual regulation

4.1 Introduction

It is well known that visual regulation strategies play a crucial role in the execution of motor precision tasks (Howard & Templeton, 1966; Welch & Warren, 1986). Over the last decades, several studies using locomotor pointing tasks such as walking or running towards and hitting or stepping onto a target emphasize the significance of visual regulation for the purpose of gait regulation (Danion et al., 2000; de Rugy et al., 2000; de Rugy et al., 2002; Franchak & Adolph, 2010; van Andel et al., 2018). It is therefore not surprising that visual regulation seems to be highly relevant for the execution of long jump run-ups, too. In fact, long jumping can be regarded as one of the most challenging locomotor pointing tasks because it requires both highest precision and optimum velocity when hitting the take-off board in order to leap as far as possible (Hay, 1986).

In their seminal paper, Lee et al. (1982) examined gait regulation mechanisms during the long jump run-up in terms of step patterns and step parameter variability. Perhaps, one of the most crucial aspects of their gait analyses was that they highlighted inter-individually different instances of highest variability (i.e., highest standard error) of toe-board distances in the run-up that were then followed by a systematic decrease of gait variability (i.e., decrease of standard error). The authors explained this decline with stride adjustments that were made due to visual regulation processes according to the estimation of time-to-contact with the take-off board. Based on these findings, Lee et al. (1982) put forth a since then influential and widely accepted classification of two phases of the long jump run-up (e.g., Glize & Laurent, 1997; Linthorne, 2008; Montagne et al., 2000): an acceleration phase including the reproduction of stereotyped gait patterns and a zeroing-in phase which consists of consecutive step adjustments that have to be made because of deviations from stereotypical behavior. Lee et al. (1982) concluded that the moment of highest variability in toe-board distance marks the transition between both phases and the initiation of visual regulation. Moreover, as gait patterns are never identical between trials, Lee et al. (1982) inferred that there has to be a continuous regulation on the basis of perceptual information to ensure precise foot positioning.

Expanding on the work by Lee et al. (1982), Hay and Koh (1988) aimed at further developing measures to evaluate an athlete's capability to meet the special requirements of the long jump run-up. Instead of using the standard error (Lee et al., 1982) as a measure of variability, Hay and Koh (1988) favored the use of the standard deviation of the toe-board distance (see also Hay, 1988), and similarly reasoned that participants adopted a visual control strategy at the point of the largest standard deviation of toe-board distance. Despite this different approach, their findings corroborated the idea of a visually controlled second run-up phase in long jumping. Examining the highest variability in foot placement by means of the maximum standard deviation (SD) of toe-board distance has prevailed over the method by Lee et al. (1982) and has become the golden standard to determine gait regulation processes during the long jump run-up. Addressing visual regulation in long jumping, Berg et al. (1994) reasoned that the increase and decrease of the SD of toe-board distance reflected a coupling of perception and action (i.e., control of actions through a coupling between an action and the perception of information in the optical flow generated by that action; Kugler & Turvey, 1988). In agreement with Lee et al. (1982), Berg et al. (1994) also argued that the increase of the SD of toe-board distance in the first phase of the approach represents a stereotyped and constant gait behavior that is naturally accompanied by deviations from this gait pattern. These inconsistencies accumulate as the approach proceeds and culminate at a certain step at which the highest SD of toe-board distance occurs. This step is suggested to demarcate the second phase of the run-up characterized by a systematic decrease of the SD of toe-board distance due to visual regulation.

Montagne et al. (2000) aimed at scrutinizing potential control mechanisms underlying the long jump run-up. They also defined the initiation of visual control by means of toe-board distance analyses but additionally conducted trial-by-trial analyses to determine the amount of step length adjustment for each trial. Their results confirmed a relationship between the step at which regulation was initiated and the amount of step length: when the spatiotemporal tolerance of the system decreased during the run-up (i.e., the perceived amount of required adjustment was high), regulation was assumed to be initiated earlier. The authors concluded that the long jump run-up is controlled by continuous processes of perception-action coupling. Similarly, de Rugy et al. (2002) argued that human locomotion is characterized by a decrease of the variability of toe-board distance and the resulting step number at which regulation is initiated and that this decrease is related to the total amount of adjustment. Panteli et al. (2016) also stated that the process of variability reduction due to visual input is based on continuous control that involves perception-action coupling. Likewise, Renshaw and Davids (2004) confirmed the notion of goal-directed gait as a continuous coupling of perception and action during locomotor pointing. Taken together, there seems to be consensus that continuous perception-action coupling plays a crucial role in controlling the long jump run-up.

In addition to the identification of the underlying control mechanisms of the long jump run-up, Bradshaw and Aisbett (2006) examined the relationship between visually guided gait regulation and jumped distance in elite long jumpers. They analyzed skilled long jumpers' step characteristics including footfall variability to identify the maximum SD of toe-board distance which they took as an indication of "*the onset of global visual regulation*". Their results showed that their gait indicator of the onset of visual regulation was closely associated with the jumped distance: the earlier visual regulation was initiated the longer the resulting jump.

To summarize, previous work on the coordination of the long jump run-up equated the point of highest variability in foot placement, i.e. the maximum SD of toe-board distance, with the "*adoption*" (Hay & Koh, 1988), "*initiation*" (Montagne et al., 2000) or "*onset*" (Bradshaw & Aisbett, 2006) of *"visual control"* or *"visual regulation"* respectively during the long jump run-up (see also Makaruk et al., 2015; Panteli et al., 2016; Panteli et al., 2014; Theodorou & Skordilis, 2012). This step was found to be closely related to step adjustment (Montagne et al., 2000) and it is assumed that this process is based on perception-action coupling (Berg et al., 1994; de Rugy et al., 2002; Montagne et al., 2000). In the following, we will refer to this parameter as "gait-based visual regulation". Interestingly, this gait-based visual regulation seems to be *"ever-present"* (Panteli et al., 2014) as it was found in novices (Berg et al., 1994; Panteli et al., 2014; Scott, Li & Davids, 1997), elite athletes (Bradshaw & Aisbett, 2006; Hay, 1988; Hay & Koh, 1988; Lee et al., 1982) and even in visually impaired long jumpers (Panoutsakopoulos et al., 2015; Theodorou et al., 2011; Theodorou et al., 2013).

Undoubtedly, the aforementioned studies examining gait-based visual regulation and the underlying control mechanisms have significantly improved our understanding of the role of gait regulation in long jump run-ups and its importance for long jump performance. Yet, it seems to be necessary to remain critical regarding the implications drawn from this parameter about visual behavior. The aforementioned studies have inferred from the maximum SD of toe-board distance and the following systematic decrease that athletes have visually guided their run-up from this point on (i.e., that they used gaze to adjust their steps). Therefore, it is surprising that there seems to be a widely accepted consensus on gait-based visual regulation as an indicator of visual behavior despite the fact that this parameter is exclusively derived from step characteristics, but not from actual gaze measures.

There has been one study so far that examined gaze direction during the long jump approach by means of assessing head orientation. Berg et al. (1993) considered the level of head and eye stabilization as important contributors to successful motor performance and reasoned that the direction of gaze affects the use of foveal and peripheral vision for the regulation of locomotor pointing tasks. Their results revealed that less experienced jumpers gazed significantly longer downwards between 0.6 to 0.2 s before take-off than more skilled jumpers. These findings led Berg et al. (1993) to suggest that more experienced jumpers might have learned to use peripheral vision to maintain an optimal body posture for take-off and that gaze direction during the long jump approach seems to depend on the level of expertise. However, an actual examination of gaze behavior by means of eye-tracking is still lacking to empirically determine whether or not gait-based visual regulation coincides with actual gaze-based measures.

To define and measure gaze-based visual regulation during the long jump approach, we suggest two alternatives: First, following the logic that the maximum variability in foot placement is argued to demarcate the *point* of the "*adoption*" (Hay & Koh, 1988), "*initiation*" (Montagne et al., 2000) or "*onset*" (Bradshaw & Aisbett, 2006) of gait-based visual regulation one might argue that this should then naturally coincide with the moment of the initial gaze on the take-off board. According to the study by Lee et al. (1982) and their two-phase model of the long jump run-up, the initial gaze on the take-off board could mark the transition between acceleration and zeroing-in phase by inducing gaze-based visual regulation for gait regulation purposes. Second, the concept of gait-based visual regulation leans on the assumption that the maximum variability in step characteristics is followed by a systematic decrease in variability controlled by visual regulation. It follows that gait-based visual regulation is seen as a mechanism to reduce variability in step characteristics to hit the take-off board properly. In research on the visual control of action and the visuomotor control of locomotor pointing, certain gaze parameters have been identified that seem to be associated with a reduction of motor variability. For instance, a meta-analysis revealed that better (in terms of more accurate, more precise, etc.) and more stable motor performance is associated with fewer fixations of longer durations in a variety of sports (e.g., badminton, soccer, golf; Mann et al., 2007). In this meta-analysis, experts exhibited fixations of 23% longer duration indicating a more purposeful pick-up of relevant information. Similarly, research on the impact of the duration of the final fixation on motor performance (referred to as the Quiet Eye; for overviews, see Vickers, 1996, 2009) seems to confirm this relationship. Among other things, it is argued that longer fixation durations and hence more stable gaze behaviors may serve the *"online control of movement"*, resulting in more stable and better performances (Klostermann et al., 2013), presumably by the reduction of movement variability. Berg et al. (1993) also argued that eye fixation could be a performance-determining factor. Now, if it were true that longer fixations may serve the reduction of motor variability, then a corollary is that gait-based visual regulation aiming at the reduction of step parameter variability (through step adjustments) should coincide with the longest gazing period on the take-off board.

Taking these previous considerations into account, the current study aims to further specify the concept of visual regulation during the long jump run-up by addressing this very question: Is gait-based visual regulation as identified in earlier work corroborated by actual measures of gaze behavior and hence identical to "gaze-based visual regulation"? If it is true that athletes *visually* hone in their run-up in long jumping from the step of maximum SD of toe-board distance, then there should be a gaze-related equivalent to gait-based visual regulation. To test this hypothesis, we conducted an eye-tracking experiment in a long jump setting.

4.2 Methods

Participants

A total of 15 participants (M_{age} = 24.3 years, SD_{age} = 2.3 years; 8 male, 7 female) who were familiar with the long jump technique volunteered to take part in the experiment. Participants were either sport science students who completed at least one athletic course as prescribed by the educational curriculum to ensure technique knowledge (n=12) or members of a local athletic team (n=3). Their reported mean personal best long jump distance was 4.98 m (*SD* = 1.06 m). All of the participants had typical vision and were in good health conditions (i.e., free from injuries, etc.). The study design was approved by the ethics committee of the Faculty of Social and Behavioral Sciences of Friedrich Schiller University Jena. Participants provided written informed consent.

Apparatus

The experiment took place at an outdoor long jump facility at the local institute of sport science with data collection from July to October. A fixed digital camera (Sony Cyber-shot RX100 v, Sony Corporation, Tokyo, Japan; recording frequency: 60 fps) was positioned on a tripod at a distance of 10 m from the take-off board (Bradshaw & Aisbett, 2006) and at a height of 1.60 m, resulting in a viewing angle of approximately 45° and a covered distance of 25 m of the run-up track (see Figure 4-1). This camera was used to record each trial for calculation of step characteristics and to perform a frame calibration upon participant's arrival. The portable eye-tracking system used in this experiment was the SMI ETG-2.6-1648-844 (SensoMotoric Instruments, Teltow, Germany; sampling frequency: 60 Hz for each eye) with a smartphone recording unit (Samsung Galaxy Note 4, Samsung Group, Seoul, South Korea). To ensure temporal synchronization of both data sources, an audio signal was provided by a mini sound system (MusicMan TXX3549, Technaxx, Frankfurt am Main, Germany). Video and eye-tracking data were transferred to a personal computer (Fujitsu LIFEBOOK E Series, Fujitsu Technology Solutions GmbH, Tokyo, Japan) for further analyses including video editing with Adobe After Effects (Adobe Inc. San José, California, United States of America), Microsoft Paint and Microsoft Excel (Microsoft Corporation, Redmond, Washington, United States of America) and BeGaze (SensoMotoric Instruments, 2018, version 3.7.60, Teltow, Germany).

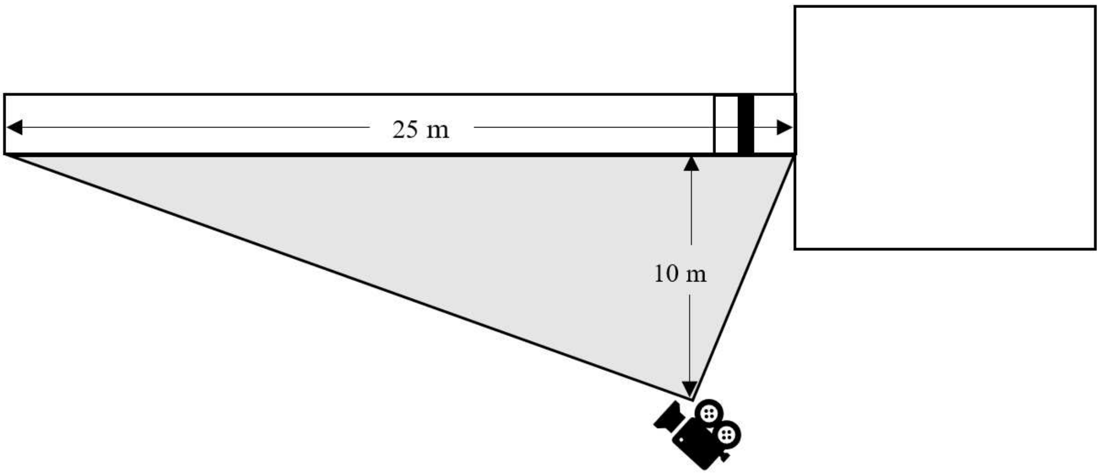

Figure 4-1. Schematic illustration of the experimental setup.

Procedure

The calibration of the run-up track for the later measurement of distances was accomplished by using a laser device (Leica Disto X310, Leica Geosystems, St. Gallen, Switzerland) that was positioned on the black line of the take-off board marking the distance of 0 m from the take-off board. Afterwards, the laser device was moved in steps of 50 cm towards the end of the run-up track to mark predefined distances relative to the take-off board (0.50 m, 1 m, 1.50 m, 2 m, etc.). A ruler attached on the laser device (i.e., facing the camera) functioned as distance marker in the frame-by-frame analyses.

Each participant completed a standardized warm-up procedure of 25 minutes which was designed by an athletics lecturer to prevent injuries. The warm-up procedure included some dynamic stretching, run-specific exercises like skipping, high knee running, and sprints as well as jump-specific exercises like standing jumps and high knee skips. Additionally, participants performed three test trials to determine their individual run-up distance (range: 15.75 m to 24.69 m). Then, the eye-tracking equipment including the SMI glasses and recording unit was attached to the participant using a chest strap. Before each trial, a three-point calibration procedure was adopted to ensure quality of the gaze data using a poster horizontally displaying three circles in different colors with a diameter of 7 cm. Circles were presented at eye height at a distance of approximately 1.50 m.

Participants had to fixate the center of each circle subsequently without head movements to calibrate the eye-tracking system.

During the experiment, participants performed six long jumps and six run-throughs (i.e., run-ups without take-off; for a similar procedure, see Bradshaw & Aisbett, 2006) to examine potential differences concerning gait and gaze related measures between these tasks. An alternating rather than randomized order of long jumps and run-throughs was selected for this experiment to rule out i) fatigue effects and ii) potential carry-over effects. Each trial started with an audio signal – a high frequent beep sound - indicating to the participants that they were free to initiate their run-up. The experimenter and an assistant consequently judged the validity of each trial's take-off position and took measures of the official jumped distances (i.e., distance from the take-off board). Note that in keeping with Bradshaw and Aisbett's investigation (2006), invalid jumps were also included into data analysis. Invalid jumps were measured from the corresponding point of take-off. After each trial, participants were instructed to rest for a minimum of three and a maximum of five minutes and to then move on to the next trial. The break between trials was also used to check on the eye-tracking system and to repeat three-point-calibration. At the end of the experiment, participants were asked to fill in a final questionnaire consisting of several demographic (age, gender, etc.) and experiment related questions (e.g., long jump experience, personal best, training frequency, take-off foot, assumed goal of the study). The experiment took approximately 60 minutes to complete per participant.

Data analysis

From our collected data, we derived measures of gait-based visual regulation (i.e., the maximum standard deviation between toe-board distances across trials) and gaze-based visual regulation, including the step of the initial gaze on the take-off board and the step of the longest gaze on the take-off board.

Data preparation for statistical processing

Gait characteristics (i.e., step length, distance to the take-off board at take-off) were calculated by identifying pixel positions for every calibrated distance through frame-by-frame analyses in Adobe After Effects and Microsoft Paint. Subsequently, these pixel positions were entered into a Microsoft Excel spreadsheet. Similarly, each trial was analyzed frame-by-frame to define the pixel positions for every footfall (i.e., distance between two successive foot touchdowns; Hay, 1988) of the run-up which were put into the same spreadsheet. Afterwards, a script in R (Version 3.6.0, R Foundation, Vienna, Austria) was used to compute the toe-to-board distances for every footfall from calibration data (i.e., the pixel positions of the marked distances and the corresponding distance values) and footfall pixel positions of every trial via quadratic functions. These values were subsequently used to calculate step characteristics (e.g., step length, step, and run-up duration). Mean standard error for distance calculation with this method was .03 m, which is similar to the reported absolute measurement error for toe-board distance by Berg et al. (1994). In accordance to the presented previous long jump research, the standard deviation (SD) of toe-board distances for each step across participants' long jumps and run-throughs respectively was calculated to identify the step of maximum SD as the onset of gait-based visual regulation (Bradshaw & Aisbett, 2006; Hay & Koh, 1988; Montagne et al., 2000).

The eye-tracking files were transferred into the BeGaze software. Our gait data analyses made it possible to assert how many milliseconds after presentation of the audio signal participants initiated their run-up. Following this procedure of temporal synchronization, it was also possible to assess the duration of every run-up from movement initiation to take-off. The corresponding time window (i.e., run-up duration) was then identified in the gaze videos to determine the mapping interval. Within the semantic gaze mapping feature of BeGaze software, four areas of interest (AOI; track, sandpit, take-off board, other) were defined to classify participants' gazes. The fourth category ("other") accounted for all gaze behaviors that were not directed at any of the other AOI. After mapping the identified time window, AOI dwell times (in %) were exported for each participant and each trial. The temporal synchronization of both data sources allowed to define the moment of the initial gaze (i.e., the first time participants gazed on the take-off board), the moment of longest gaze on the take-off board (i.e., the gaze with the longest dwell time on the take-off board), as well as the corresponding step before take-off for these gaze events for each trial and participant as potential markers of gaze-based visual regulation. Mean values for these variables were then calculated for each participant out of six trials according to the condition. For long jumps 96.61 % and for run-throughs 99.88 % of participants' dwell times could be tracked successfully, resulting in a total of 3.5 % loss of gaze data.

Statistical analysis

Data analyses were conducted using SPSS 25 (International Business Machines Corporation, Armonk, New York, United States of America). First, we controlled for potential outliers regarding participants' jumping performance. That is, we calculated their mean percentage personal best (across trials and for each trial) and checked whether their mean percentage personal best varied more than two standard deviations from their reported personal best. As we could not identify any outliers, data of 90 long jumps (81.1 % valid) as well as 90 run-throughs (77.8 % valid) were included in the data analysis.

To examine whether the step of gait-based regulation coincides with gaze-based regulation in terms of the step of the initial gaze on the take-off board, we conducted a 2 (condition: long jump vs. run-through) by 2 (type of regulation: step of gait-based visual regulation vs. step of the initial gaze on take-off board) ANOVA. The same ANOVA was run for the longest gaze on the take-off board to test whether the step of gait-based visual regulation coincides with the step of the longest gaze on the take-off board as a measure of gaze-based visual regulation.

Because Bradshaw and Aisbett (2006) reported a relationship between gait-based visual regulation and jumped distance, we also calculated Pearson's product moment correlations[3] between gait-based visual regulation and jumped distance as well as between gaze-based visual regulation and jumped distance. Additionally, we conducted a 2 (condition: long jump vs. run-through) by 4 (dwell times on AOIs: sandpit, take-off board, track, other) ANOVA to test whether gazing at the four AOIs depended on condition.

Considering the range of participants' run-up distances, we additionally examined whether the comparison between shorter and longer run-ups affected the relationship between gait-based and gaze-based visual regulation. To this end, we conducted a median split to divide our participants into two groups (short run-

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[3] In keeping with the comment of an anonymous reviewer, we additionally calculated Spearman's ρ as this statistical procedure accounts for both continuous and categorical variables.

up vs. long run-up) according to their run-up distances across conditions: short (n = 7) and long run-ups (n = 8). We then ran a 2 (condition: long jump vs. run-through) by 2 (type of regulation: step of gait-based visual regulation vs. step of the initial gaze on take-off board) by 2 (group: short run-up vs. long run-up) ANOVA. We conducted the same ANOVA for type of visual regulation with step of gait-based visual regulation vs. step of the longest gaze on take-off board respectively.

The effect size for analyses of variance is reported as partial eta squared (η_p^2) and for correlational measures as Pearson's correlation coefficient r. According to Cohen and Cohen (1983), partial eta squared (η_p^2) values represent either small (.01), medium (.06), or large effects (.14). Alpha was set at .05 for all statistical analyses.

4.3 Results

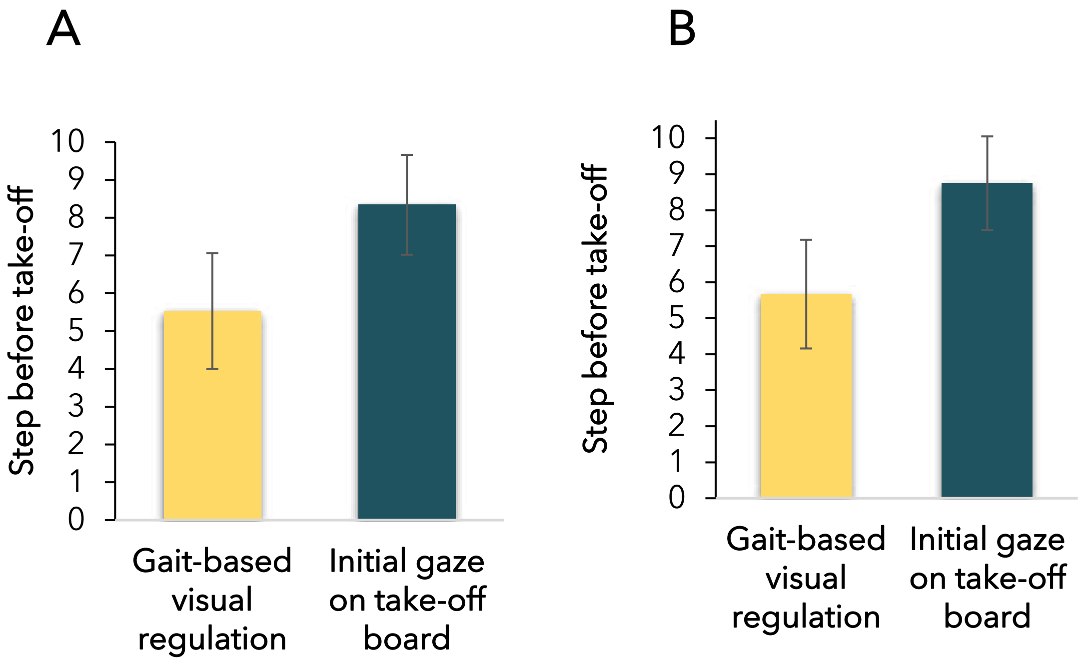
Participants' self-reported personal best (PB), as well as their mean percentage personal best (Mean %PB), are reported in Table 4-1.

Table 4-1. Reported personal best and mean percentage personal best (SD) reached by each participant.

Participant	PB in m	Mean %PB
1	6.29	76 (4.9)
2	6.51	75 (3.5)
3	4.27	72 (5)
4	3.84	89 (6.5)
5	5.80	74 (7.3)
6	4.75	95 (2.7)
7	3.00	90 (5.5)
8	6.10	81 (1.3)
9	4.27	74 (4)
10	6.39	71 (8.3)
11	4.75	75 (3.8)
12	4.10	93 (1.6)
13	5.20	77 (5.4)
14	4.17	72 (6.9)
15	5.20	83 (3.5)

The first 2 (condition: long jump vs. run-through) by 2 (type of regulation: step of gait-based visual regulation vs. step of initial gaze on the take-off board) ANOVA revealed neither a significant main effect for condition ($F(1,14) = .34$, $p = .567$, $\eta_p^2 = .02$) nor a significant interaction ($F(1,14) = .07$, $p = .801$, $\eta_p^2 = .01$). However, there was a significant main effect for type of regulation ($F(1,14) = 11.94$, $p = .004$, $\eta_p^2 = .46$). This effect indicates that the step of the initial gaze on the take-off board was realized earlier, on average 8.34 steps ($SD = 2.61$ steps) from the take-off board for long jumps and 8.75 steps ($SD = 2.59$ steps) from the take-off board for run-throughs, than the step of gait-based visual regulation that was initiated on average 5.53 steps ($SD = 3.02$ steps) from the take-off board for long jumps and on average 5.67 steps ($SD = 2.99$ steps) from the take-off board for run-throughs (Figure 4-2A and 4-2B).

By contrast, the 2 (condition: long jump vs. run-through) by 2 (type of regulation: step of gait-based visual regulation vs. step of longest gaze on the take-off board) ANOVA yielded neither a significant main effect for condition ($F(1,14) = 1.10$, $p = .312$, $\eta_p^2 = .07$) nor for type of regulation ($F(1,14) = .08$, $p = .781$, $\eta_p^2 = .01$). There was also no significant interaction ($F(1,14) = .61$, $p = .449$, $\eta_p^2 = .04$). In comparison to gait-based regulation the longest gaze on take-off board appeared on average 5.33 steps (*SD* = 2.19 steps) from the take-off board for long jumps and 6.28 steps (*SD* = 1.84 steps) from the take-off board for run-throughs. Hence, the step of the longest gaze on take-off board did not differ from the step of gait-based visual regulation for both long jumps and run-throughs (see Figure 4-2C and 4-2D).



Long Jumps

Run-throughs

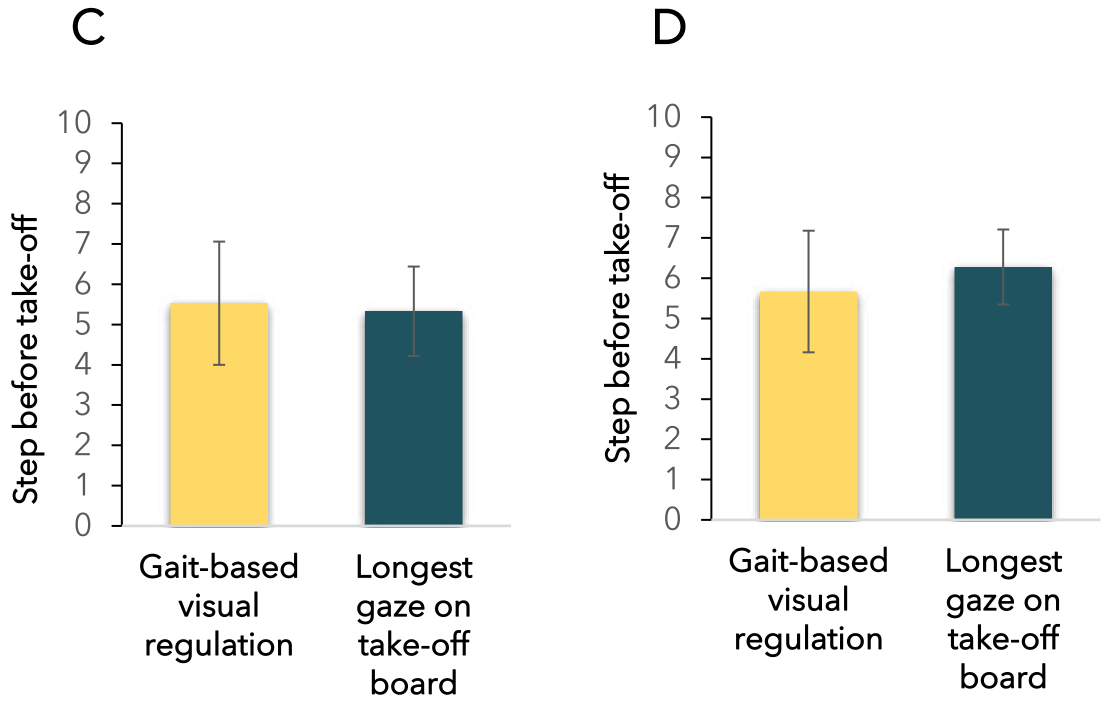


Figure 4-2. Comparison between gait-based visual regulation (i.e., step of maximum standard deviation of toe-board distance) and gaze-based visual regulation in terms of step of initial gaze on take-off board for long jumps (A) and run-throughs (B) and step of longest gaze on take-off board for long jumps (C) and run-throughs (D). Error bars indicate 95% confidence intervals.

There was no significant correlation between gait-based visual regulation and jumped distance (*r* = .095, *p* = .737). Equally, the gaze-based measures namely initial gaze on take-off board (*r* = -.169, *p* = .547) and longest gaze on take-off board (*r* = .041, *p* = .884) were not significantly associated with jumped distance.[4]

The 2 (condition: long jump vs. run-through) by 4 (dwell times on AOIs: sandpit, take-off board, track, other) ANOVA showed no significant interaction (*F* (1,14) = .22, *p* = .650, η_p^2 = .02), indicating that the percentage dwell times for the four AOIs were not differently affected by condition (Table 4-2).

Table 4-2. Descriptive statistics for all dependent measures separated by condition (long jump vs. run-through) including means (M) and standard deviations (SD) as well as the 95% confidence intervals (CI).

Parameter	Long jumps (n = 90) [95 % CI]	Run-throughs (n = 90) [95 % CI]
Jumped distance in m	3.89 (.73) [3.52, 4.26]	-
Step length in m	1.53 (.20) [1.43, 1.63]	1.52 (.20) [1.42, 1.62]
Distance to board at take-off in m	.14 (.15) [.06, .22]	.17 (.16) [.06, .25]
Dwell time on sandpit in %	20.63 (10.41) [15.36, 25.9]	18.11 (7.94) [14.09, 22.13]
Dwell time on take-off board in %	12.73 (6.67) [9.35, 16.11]	15.49 (9.31) [10.77,18.21]
Dwell time on track in %	44.03 (16.20) [35.82, 52.24]	45.11 (14.85) [37.59, 52.63]
Dwell time on other in	19.22 (11.70)	21.17 (12.75)

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[4] The calculation of Spearman's ρ confirmed the results as reported above. There was no significant correlation between jumped distance and the step of gait-based visual regulation (*Spearman's* ρ = 0.054, *p* = .847). Likewise, the step of the initial gaze on the take-off board (*Spearman's* ρ = −0.227, *p* = .416) and the step of the longest gaze on the take-off board (*Spearman's* ρ = −0.093, *p* = .742) were not significantly correlated with jumped distance.

%	[13.29, 25.15]	[14.71, 27.63]
Step of gait-based visual regulation	5.53 (3.02) [4,7.06]	5.67 (2.99) [4.16, 7.18]
Step of initial gaze on the take-off board	8.34 (2.61) [7.02, 9.66]	8.75 (2.59) [7.45, 10.05]
Step of longest gaze on the take-off board	5.33 (2.19) [4.22, 6.44]	6.28 (1.84) [5.35, 7.21]

Finally, regarding the question whether shorter vs. longer run-ups affected the relationship between gait-based and gaze-based visual regulation, the first 2 (condition: long jump vs. run-through) by 2 (type of regulation: step of gait-based visual regulation vs. step of the initial gaze on take-off board) by 2 (group: short run-up vs. long run-up) ANOVA confirmed the significant main effect for type of regulation, the non-significant main effect for condition and the non-significant interaction between both factors as reported by the 2 x 2 ANOVA above. Further, the analysis revealed neither significant two-way interactions between condition and group (F(1,14) = .02, p = .898, η_p^2 = .001) nor between type of regulation and group (F(1,14) = .001, p = .978, $\eta_p^2 < .001$), nor a significant three-way interaction for condition, type of regulation and group (F(1,14) = .354, p = .562, η_p^2 = .03). However, there was a significant main effect for group (F(1,14) = 13.30, p = .003, η_p^2 = .51), indicating that gait-based visual regulation and the initial gaze on the take-off board occurred at different steps before take-off depending on the length of the run-up (see Figure 4-3A and 4-3B).

The second 2 (condition: long jump vs. run-through) by 2 (type of regulation: step of gait-based visual regulation vs. step of longest gaze on the take-off board) by 2 (group: short run-up vs. long run-up) ANOVA similarly confirmed the null effects for the factors condition and type of regulation as presented in the corresponding 2 x 2 ANOVA above. Additionally, there were no significant interactions between condition and group (F(1,14) = .003, p = .957, $\eta_p^2 < .001$), type of regulation and group (F(1,14) = .228, p = .641, η_p^2 = .02) as well as no three-way interaction between condition, type of regulation and group (F(1,14) =

.641, p = .438, $\eta_p{}^2$ = .05). Again, the ANOVA showed a significant main effect for group (F (1,14) = 10.78, p = .006, $\eta_p{}^2$ = .453), illustrating that gait-based visual regulation and the longest gaze on the take-off board occurred at different steps before take-off depending on the length of the run-up (see Figure 4-3C and 4-3D).

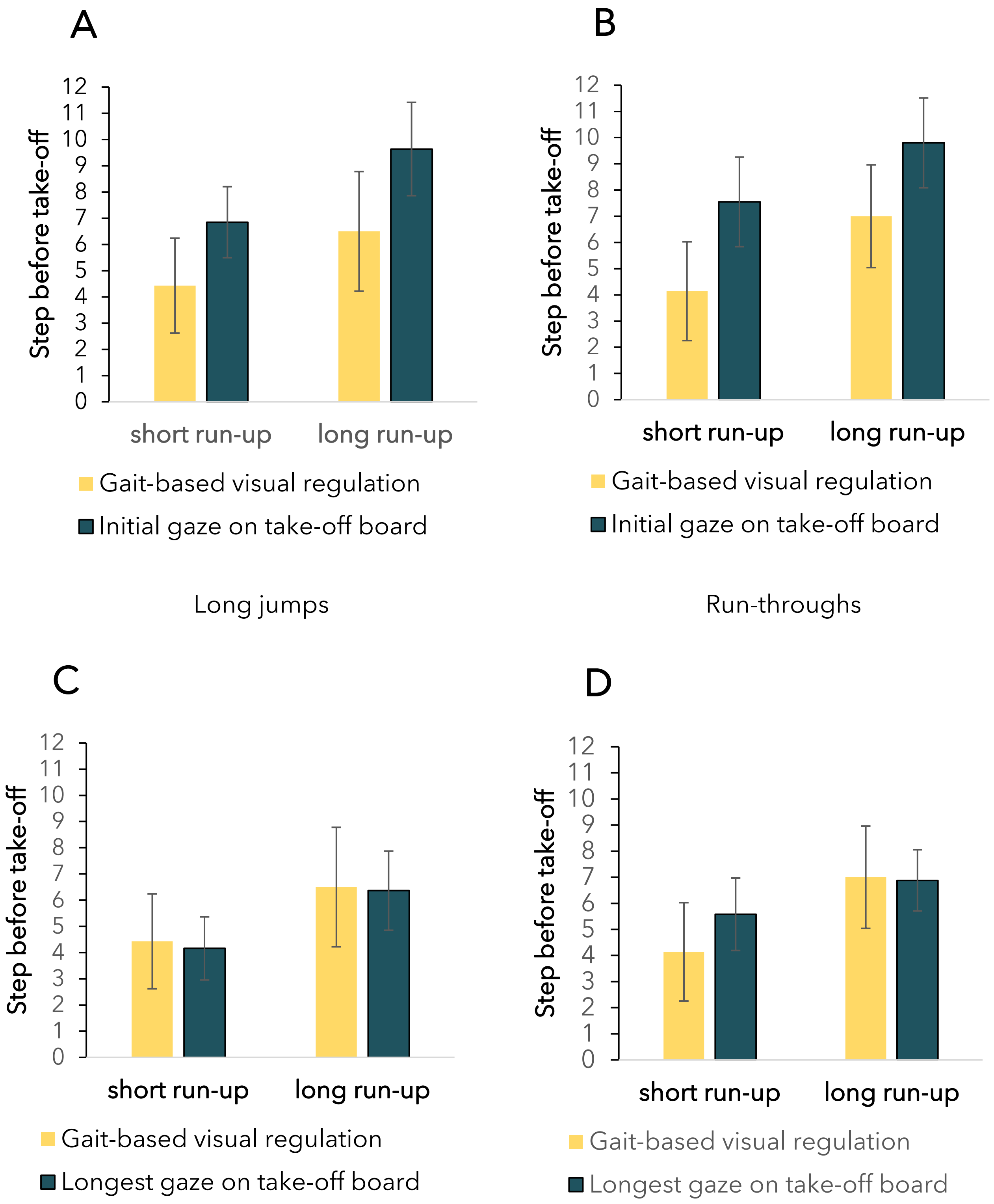

Figure 4-3. Comparison between gait-based visual regulation (i.e., step of maximum standard deviation of toe-board distance) and gaze-based visual regulation in terms of step of initial gaze on take-off board for long jumps (A) and run-throughs (B) and step of longest gaze on take-off board for long jumps (C) and run-throughs (D) separated for participants with a short and a long run-up. Error bars indicate 95% confidence intervals.

4.4 Discussion

Besides playing a crucial role for the execution of motor precision tasks in general (Howard & Templeton, 1966; Welch & Warren, 1986) and for gait regulation purposes in locomotor pointing tasks in specific (Danion et al., 2000; de Rugy et al., 2000, 2002; Franchak & Adolph, 2010; van Andel et al., 2018), there can be no doubt that visual regulation is also particularly important in long jumping. Nevertheless, the mechanisms of visual control during long jumping have not been conclusively determined yet. Starting with Lee et al. (1982), a plethora of studies argued in favor of gait-based visual regulation and relied exclusively on the step of maximum SD of toe-board distance as the indicator of visual regulation initiation (Berg et al., 1994; Bradshaw & Aisbett, 2006; Hay, 1988; Hay & Koh, 1988; Makaruk et al., 2015; Panteli et al., 2014, 2016; Scott et al., 1997; Theodorou et al., 2011; Theodorou & Skordilis, 2012). As there has only been one study so far by Berg et al. (1993) that indirectly examined gaze direction in long jumping by means of assessing head orientation, the current study aimed to compare gait-based visual regulation measures to measures of actual gaze behavior.

Our results revealed that gait-based visual regulation did not coincide with the step at which the initial gaze on take-off board was observable. However, the step at which the longest gazing period on the take-off board (i.e., longest dwell time on target) was initiated and the parameter of gait-based visual regulation did, in fact, coincide. Based on the assumption that longer gaze durations are related to better (i.e., more accurate, more precise, etc.) and more stable motor performance (Mann et al., 2007; Vickers, 1996, 2009), this finding might be taken to confirm the hypothesis that fixations of longer duration, in the present study expressed by dwell times, serve the "online control of movement" (Klostermann et al., 2013) and are associated with a reduced variability of the locomotor pattern in long jumping. To the best of our knowledge, the present study is the first to show that the step at which the longest gazing period on the take-off board (i.e., longest dwell time on target) was initiated seems to play an important role in visually regulating the long jump run-up. Hence, it adds to the seminal work by Berg et al. (1993) that indirectly examined gaze direction in long jumping by means of assessing head orientation and concluded that eye fixation could be a performance-determining factor in locomotor pointing tasks in general, and long jumping in specific. Additionally, the coincidence between the parameter of gait-based visual regulation (i.e., the transition to the zeroing-in phase of the run-up including the reduction of motor variability) and the longest gaze on the take-off board (i.e., visual input serving the reduction of motor variability) seems to support perception-action coupling as a driving mechanism in locomotor pointing (de Rugy et al., 2002; Panteli et al., 2016; Renshaw & Davids, 2004). That is, goal-directed locomotion involves a continuous coupling of perception and action that also plays a crucial role in controlling the long jump run-up.

In addition to the comparison between gait-based and gaze-based visual regulation, we also examined whether visual regulation strategies are related to jumped distance as Bradshaw and Aisbett (2006) reported an earlier and hence longer lasting gait-based visual regulation to be closely intertwined with longer jumps. Our results did not confirm their findings. We argue that this difference might be due to the differences between our and Bradshaw and Aisbett's (2006) sample. The novice participants in our study, predominantly sport science students with little experience with long jumping, were by no means comparable to trained or elite athletes as in Bradshaw and Aisbett (2006). Moreover, in contrast to previous studies (Bradshaw & Aisbett, 2006; Panteli et al., 2016), our sample did not display significant differences regarding the step of gait-based visual regulation between long jumps and run-throughs. Bradshaw and Aisbett (2006) reasoned that gait regulation patterns differ between long jumps and run-throughs because run-throughs do not require an actual take-off. Therefore, run-throughs are supposed to be less demanding for visual regulation and hence their execution is said to be different from long jumps. Although this hypothesis may apply to elite jumpers and trained long jumpers, it might not be valid for less experienced participants who may perhaps not differentiate between the implementation of long jumps and run-throughs as much as experts do. Regarding the properties of our sample, it seems that individual constraints (i.e., level of expertise) had a greater impact on task execution in general than different task demands per se. This assumption may be further supported by our gaze data analyses showing that there was neither a significant correlation between gaze measures and jumped distance, nor did the conditions, long jumps vs. run-throughs, differently affect percentage dwell times for the different gaze locations (i.e., AOIs). However, if expertise is a determining factor in this regard, we cannot rule out that an expert sample might show a pattern of gaze that significantly differs from the gaze data we found in the current study.

Given the range of participants' run-up distances, we ran additional analyses to test whether short run-ups vs. long run-ups affected the relationship between gait-based and gaze-based visual regulation. First and foremost, the results showed that separating the participants in two groups based on the length of their run-ups did not affect the relationship between gait-based and gaze-based visual regulation. That is, the step of the initial gaze on the take-off board was realized earlier than the step of gait-based visual regulation, independent of condition and run-up distance, while the step of the longest gaze on the take-off board did not differ from the step of gait-based visual regulation, irrespective of condition and run-up distance. The significant main effect of run-up distance in both ANOVAs indicated that our gait-based and gaze-based measures occurred at different steps before take-off depending on the length of the run-up, which is to be expected and may be attributable to different velocity demands coming along with different run-up distances. Evidence for this assumption can be found in studies by Aoyama et al. (1996) and Nemtsev et al. (2014) which confirmed that different run-up lengths and consecutively adjusted velocities during the long jump are associated with changes in kinematic measures like take-off angle or step length.

Importantly, our findings are generally in agreement with previous studies that examined gait regulation processes in novice or non-expert long jumpers (Berg et al., 1994; Scott et al., 1997; Panteli et al., 2014) in that gait-based visual regulation is not an exclusive attribute of expert performance. In keeping with these studies, we argue that gait-based visual regulation may not be due to learning processes per se but represents a natural means of gait control in the sense of an *"ever-present"* feature (Panteli et al., 2014). Nonetheless, to corroborate this assertion, we call for replications of our work that include an expert sample of long jumpers.

Having said this, clearly more research is necessary to further specify the relationship between gait-based and gaze-based visual regulation to improve our understanding of visual regulation in long jump run-ups in specific and locomotor pointing tasks in general. Apart from potential expert-novice differences scrutinized above, we critically discuss limitations of the research field in general and our study in specific in the remainder of the discussion and consequently derive three suggestions for future research that address i) theoretical advancements, ii) issues of empirical validity and iii) methodological challenges.

First, in the current study we adopted the method to identify gait-based visual regulation by equating the point of highest variability in foot placement, i.e. the maximum SD of toe-board distance, as an indicator of visually *"honing in"* the foot placements to the take-off board (Bradshaw & Aisbett, 2006; Hay & Koh, 1988; Montagne et al., 2000). Yet, this method has been criticized for neglecting the fact that visual regulation during the long jump run-up may rather be a continuous perception-action coupling process (de Rugy et al., 2002; Montagne et al., 2000). We agree that to ultimately improve our understanding of the mechanisms underlying visual regulation during the long jump run-up, future research would be well advised to embrace different theoretical views including perception-action coupling and to be more inclusive regarding the variety of methodological approaches to assess gait and gaze measures in locomotor pointing. An additional route for future research to shed light on the visual control mechanisms underlying the long jump run-up we deem fruitful is to examine both inter- and intra-individual differences in (visually) regulating the long jump run-up.

Second, concerning the empirical validity of the reported findings in the literature on the visual regulation of the long jump, we argue that this field of research is generally characterized by relatively small sample sizes, including the studies of Lee et al. (1982) with n = 3, Scott et al. (1997) with n = 11, Bradshaw and Aisbett (2006) with n = 6, Theodorou et al. (2011) with n = 10, Theodorou and Skordilis, (2012) with n = 7, Panteli et al. (2016) with n = 7 and our study with n = 15. Although our sample size of 15 participants slightly exceeds sample size of previous studies, future studies should try to extend the sample size to be able to draw more reliable and valid conclusions.

Finally, Berg et al. (1993) concluded that peripheral vision also seems to be important for the execution of long jump run-ups, especially for more experienced jumpers. Again, this finding emphasizes the need for a further evaluation of novice-expert differences as it is biomechanically recommended to avoid gazing down towards the board at take-off to maintain an adequate body posture for the take-off (Berg et al., 1993). A limitation of mobile eye-tracking technology consists in the fact that it can only measure foveal vision. Methods to assess the use of peripheral information during the long jump have yet to be developed. Until then, we recommend that future studies might additionally monitor head movements and orientation (Berg et al., 1993; Bradshaw & Aisbett, 2006; Durant & Zanker, 2020) by combining kinematic measures with gaze measures to examine interactions between head orientations and gaze orientations (see Mann et al., 2013). Moreover, to reduce the absolute measurement error for the calculation of toe-board distances, future research would be well-advised to use a panned instead of a fixed camera setup.

In conclusion, gait-based visual regulation (reduction of motor variability) and gaze-based visual regulation (executing visual control for zeroing-in on the take-off board) appear to be equal if gaze-based visual regulation is defined as the step of the longest gaze on the take-off board. This finding indicates that the relationship between gait-based and gaze-based visual regulation is depending on the parameter taken to resemble gaze-based visual regulation. The coincidence between gait-based visual regulation and the longest gaze on the take-off board might imply that longer gazing periods on the take-off board may be used to reduce motor variability and to prepare the athlete for the best possible take-off. Surely, these findings require further investigation to validate their robustness across different groups of participants (e.g., elite athletes) before deriving specific coaching implications and designing visual training programs for athletes. Nonetheless, our results may provide initial insights into the gazing behavior during the long jump run-up that may be used to guide practitioners including coaches, teachers, etc. on how to instruct athletes to visually regulate their run-ups and to improve learning and performance.

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CHAPTER 5

EFFECTS OF AUDITORY FEEDBACK IN LONG JUMPING

5 STUDY 2: EFFECTS OF AUDITORY FEEDBACK ON GAIT BEHAVIOR, GAZE PATTERNS AND OUTCOME PERFORMANCE IN LONG JUMPING

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Abstract

In the current study, we conducted two experiments to investigate the impact of concurrent, action-induced auditory feedback on gait patterns, gaze behavior and outcome performance in long jumping. In Experiment 1, we examined the effects of present vs. absent auditory feedback on gait, gaze, and performance outcome measures. Results revealed a significant interaction effect between condition (present vs. absent auditory feedback) and phase (acceleration vs. zeroing-in phase) on participants' step lengths indicating that the absence (rather than the presence) of auditory feedback led to facilitatory effects in terms of a more prototypical gait pattern (i.e., shorter steps in the acceleration phase and longer steps in the zeroing-in phase). Similarly, the absent auditory feedback led to a higher gaze stability in terms of less switches between areas of interest (AOIs). However, there was no effect on jumped distance. In Experiment 2, we scrutinized the influence of concurrent vs. delayed auditory feedback on all three performance parameters. In contrast to concurrent feedback, delayed auditory feedback negatively affected all three measures: participants showed (i) dysfunctional deviations from their prototypical gait pattern (i.e., shorter steps across both phases of the run-up), (ii) less stable, maladaptive gaze patterns (i.e., more switches between AOIs) and (iii) poorer jumping performance (i.e., shorter jumped distances). Together, the two experiments provide clear evidence for the impact of concurrent, action-induced auditory feedback on the coordination of complex, rhythmical motor tasks such as the long jump.

Keywords: Multisensory integration; Motor performance; Gaze behavior

5.1 Introduction

Perception is multisensory in nature (Auvray & Spence, 2008; Calvert et al., 2004; Driver& Spence, 2000). An impressive, early demonstration of perception's multisensory character was provided by McGurk and MacDonald (1976). In their seminal study, matching faces articulating, for instance, a syllable *ga* with voices articulating another syllable *ba* led observers to perceive the syllable *da*. This example of multisensory integration, nowadays referred to as the McGurk effect, can be explained by the interaction and synthesis of information from two (or more) sensory modalities (Stein & Stanford, 2008). In particular, the McGurk effect emphasizes the bidirectional relationship between the visual and the auditory modality which has been subjected to a plethora of studies (cf. Soto-Faraco et al., 2005; Spence, 2007). In addition, in a recent review, Stanton and Spence (2020) concluded that auditory information also affects (i) body perception (cf. Stanton et al., 2018; Tajadura-Jiménez et al., 2017; Tajadura-Jiménez et al., 2018), (ii) the perception of bodily movements (cf. Furfaro et al., 2015; Melaisi et al., 2018), and (iii) motor behavior (cf. Drost et al., 2005; Murgia et al., 2015).

Over the past few decades, research on the influence of auditory feedback on motor outcomes has grown consistently. For instance, Castiello et al. (2010) provided evidence that congruent auditory feedback (i.e., sounds that veridically represent a person's motor behavior) actually increased participants' grasping behavior in terms of shorter movement durations and more accurate motor responses, whereas incongruent auditory feedback (i.e., sounds that represent another motor behavior) decreased participants' performance. Similar facilitatory effects of congruent auditory feedback were also reported by Danna et al. (2015) showing that participants consistently improved their handwriting kinematics of new characters written with their non-dominant hand when supported by auditory feedback. In contrast, findings by Drost et al. (2005) revealed that pianists were more likely to produce erroneous sequences in the presence of incongruent auditory input. With respect to these findings, Castiello et al. (2010) inferred that the sounds of contact cues are incorporated instantly within the internal model of a motor action, thereby eliciting either facilitatory effects (i.e., successful integration of information for the same motor plan) or interference effects (i.e., response uncertainty). These assumptions are also supported by the idea of a multisensory feedforward system (cf. Wolpert & Ghahramani, 2000) in which executed movements are compared with intended movements using information from different sensory modalities (e.g., the auditory modality) resulting in a consistent update process of the corresponding internal model of a certain movement.

The findings by Castiello et al. (2010), Danna et al. (2015), and Drost et al. (2005) are indicative of a substantial impact of auditory feedback on the execution of motor tasks. However, the tasks presented within the reported studies (e.g., grasping, writing) were characterized by rather low task complexities as they mainly concentrated on the upper limbs without requiring orientation or balance of the full body. Interestingly, Chase et al. (1961) argue that task complexity, temporal complexity in particular, determines the sensitivity of a task to (modified) auditory feedback. Furthermore, MacPherson et al. (2009) suggest that tasks with temporally demanding, rhythmical movement patterns may be specifically sensitive to auditory feedback. The question arising from these previous considerations is therefore how more complex motor tasks are affected by different types of auditory feedback.

In fact, a current review on the relationship between sound and movement in sports by Schaffert et al. (2019) reported effects of concurrent, action-induced auditory feedback (e.g., the sound emanating from racquet-ball contact in tennis, Cañal-Bruland et al., 2018) on the sense of agency (Murgia et al., 2012; Kennel et al., 2014), action anticipation (Allerdissen et al., 2017; Camponogara et al., 2017; Cañal-Bruland et al., 2018; Müller et al., 2019; Sors et al., 2017) and motor learning (Pizzera et al., 2017). As highlighted in this review, the facilitating effects of congruent auditory feedback as well as the interference effects of incongruent auditory feedback on motor performance as previously reported (e.g., Castiello et al., 2010; Drost et al., 2005), have not only been shown in the lab, but also in the field of sports.

For instance, Agostini et al. (2004) impressively demonstrated that hammer throwers improved their motor performance (i.e., larger throwing distances) and task execution (i.e., more standardized movement pattern with less variability across trials) when provided with action-induced rhythmic sounds (i.e., the sound produced by the contact between hammer and air) associated to their best personal throw. According to Agostini et al. (2004), these findings underpin the crucial role of auditory information for the timing of body locomotion (cf. Effenberg, 1996) and the importance of (matching) acoustic stimulation to induce mental representations of motor processes and to update the internal model of motor action respectively.

Within a similarly complex motor task but focusing on the effects of incongruent auditory feedback, Kennel et al. (2015) illustrated that delayed auditory feedback significantly affected participants' movement performance (i.e., slower overall times) and movement stability (i.e., deviations from the ideal gait pattern) in hurdle jumping. As stated by Kennel et al. (2015), these findings outline a direct effect of auditory feedback on motor performance and support the notion of human's sensitivity to footstep sounds as introduced by Menzer et al. (2010). Further, to explain their results, Kennel et al. (2015) also refer to the model by Desmurget and Grafton (2000) on internal feedback loops. Internal feedforward models of a certain action are continuously updated on the basis of sensory input and motor output to assess motor commands. In terms of delayed auditory feedback, the expected sensory input diverges from the actually perceived sensory input, thereby leading to modified movement patterns.

Apart from the examination of congruent vs. incongruent auditory feedback, another approach was put to the test by Schaffert et al. (2020) in the context of rowing. In their investigation, participants displayed higher standard deviations in their stroke frequencies when deprived of auditory feedback compared to present auditory feedback. Following the reasoning of Schaffert et al. (2020), these findings provide evidence that action-induced auditory feedback comprises relevant feedback about temporal aspects of movement control for the purpose of error correction during performance.

To summarize, previous studies on the impact of naturalistic auditory feedback have revealed both positive and negative effects on motor performance.

First, congruent auditory feedback (i.e., sounds veridically representing a certain motor behavior) facilitated aspects of motor execution in simple motor tasks such as grasping (Castiello et al., 2010) and writing (Danna et al., 2015) as well as in complex motor tasks such as hammer throwing (Agostini et al., 2004). Second, incongruent auditory feedback (i.e., modified, non- veridical sounds) led to a decreased motor performance in different contexts such as piano playing (Drost et al., 2005), grasping (Castiello et al., 2010) and hurdle jumping (Kennel et al., 2015). Third, motor performance in a complex task such as rowing was negatively influenced by the absence of auditory feedback when compared to present auditory feedback conditions (Schaffert et al., 2020). Apart from these naturalistic forms of acoustic feedback, there is growing evidence that motor learning and execution can also benefit from rather artificial auditory feedback in terms of movement sonification (i.e., sonification of motor parameters such as kinematics) within a variety of sports (for an overview, see Schaffert et al., 2019).

Recent research on the impact of auditory feedback on motor parameters clearly indicates that auditory information significantly adds to the updating process of movement representations. From a neurophysiological perspective, these findings might be anchored in the close interactions between auditory and motor areas of the brain. More specifically, Fogassi and Gallese (2004) identified polymodal neurons in the premotor cortex which can be activated by a variety of sensory inputs. Additionally, Gazzola et al. (2006) found similar patterns of activation in the ventral premotor cortex for both the execution of a motor action and the listening to the sound of this action. As a matter of fact, there is a plethora of studies (cf. Crasta et al., 2018; Large & Snyder, 2009) showing that the mere listening to auditory (rhythmic) stimuli can induce a synchronized oscillation of auditory and motor neurons (i.e., auditory-motor entrainment) resulting in more efficient internal representations of movement (Effenberg et al., 2016; Shams and Seitz, 2008) and improved online error-corrections (Hossner et al., 2015).

In a similar vein, Morillon and Baillet (2017) showed that auditory stimuli serve to generate accurate temporal predictions on action. The particular impact of auditory information on temporal aspects of action prediction and execution is further supported by evidence showing a higher sensitivity of the auditory system to temporal information and a dominance of the auditory system in timing tasks (Stauffer et al., 2012; for a recent discussion on the sensitivity of the auditory vs. visual systems to temporal vs. spatial information, see also Loeffler et al., 2018). Accordingly, sports with complex rhythmical movement patterns (such as hammer throwing or hurdle jumping) might be particularly sensitive to auditory feedback due to their temporal dynamics (see Gallahue & Donnelly, 2003; MacPherson et al., 2009; Schaffert et al., 2010). In this regard, Schaffert et al. (2019) recently argued that concurrent, action-induced auditory feedback has a strong impact on motor performance in complex tasks because (i) auditory reafferences are consistently disposable to the listener (Gaver, 1993), and (ii) transport crucial information about temporal aspects of movements (Sigrist et al., 2013), thereby providing relevant task-related feedback (Dubus & Bresin, 2013; Sors et al., 2015).

Although previous studies have undoubtedly contributed to our understanding of the effects of auditory feedback on motor behavior, the behavioral mechanisms mediating the effects of, for instance, the presence vs. absence of auditory information (Schaffert et al., 2020) or the impact of delayed auditory feedback (Kennel et al., 2015) on motor performance (i.e., outcome performance) remain yet to be determined. Therefore, going beyond mere measures of outcome performance such as thrown distances (Agostini et al., 2004), and next to focusing on motor control parameters such as step characteristics (Kennel et al., 2015) or stroke frequencies (Schaffert et al., 2020), in the current study, we examined to what degree gaze behavior may modulate the impact of auditory information on complex motor behavior. The reasons for examining gaze behavior were twofold: (i) it is well known that gaze behavior is crucially linked to motor performance (e.g., Klostermann et al., 2013; Klostermann & Moeinirad, 2020; Mann et al., 2007), and (ii) it is equally well known that auditory information can also directly affect visual processes (see the introductory example of the McGurk effect; for an overview, see e.g. Shams et al., 2004; Watanabe & Shimojo, 2001).

Bearing in mind MacPherson et al.'s (2009) suggestion that rhythmical movement patterns may be particularly sensitive to auditory feedback, for the purpose of our study, we identified the long jump as an excellent experimental testbed. Long jumping is characterized by a rhythmical run-up to the take-off board, in which high velocities and optimal precision need to be met to leap as far as possible. In addition, both gait characteristics (e.g., Bradshaw & Aisbett, 2006; Hay, 1988; Scott et al., 1997), as well as gaze characteristics (e.g., Hildebrandt & Cañal-Bruland, 2020), have been identified to play crucial roles in long jumping. To examine the impact of auditory information on all three measures, that is, motor control parameters (i.e., gait patterns), gaze parameters, and outcome performance, we ran two experiments. Experiment 1 aimed at examining whether and if so how the presence (vs. absence) of concurrent auditory feedback (i.e., action-induced sounds) adds to and affects the three performance measures. Expanding on Kennel et al. (2015), Experiment 2 aimed at testing the impact of delayed auditory feedback.

5.2 Experiment 1

Previous research on the relationship between auditory information and movement (see Schaffert et al., 2019; Stanton & Spence, 2020) emphasized the importance of concurrent action-induced auditory feedback for action execution in terms of a facilitation of motor performance in complex motor tasks (Agostini et al., 2004; Castiello et al., 2010; Kennel et al., 2015). In addition, Schaffert et al. (2020) recently reported negative effects of absent auditory feedback on movement precision in rowing. However, as highlighted above, whether and if so how the presence vs. absence of auditory feedback influences gait and gaze parameters as well as outcome performance remains to be determined. Therefore, in Experiment 1 we examined the effects of present vs. absent auditory feedback on participants' gait behavior (i.e., step length), gaze patterns (i.e., dwell times on areas of interest (AOIs), number of switches between AOIs; see e.g., Baurès et al., 2015; Binsch et al., 2009; Milazzo et al., 2016; Van Maarseveen et al., 2018) and their outcome performance in long jumping (e.g., Bradshaw and Aisbett, 2006). In agreement with Lee et al. (1982), and to allow for a more fine-grained analysis, we considered the two phases of the long jump run-up, that is, the *acceleration* and the *zeroing-in* phases, separately. Within this two-phase model by Lee et al.

(1982), both phases serve different purposes and are characterized by different gait patterns. While fast and short steps are necessary to build up adequate velocity during the acceleration phase, the zeroing-in phase requires long and adjusting steps to hit the take-off board properly. Consequently, while gait variability changes across these phases, the occurrence of maximum gait variability followed by a systematic decrease is said to mark the transition between acceleration and zeroing-in phase (cf. Hay & Koh, 1988).

To examine the influence of the presence vs. absence of auditory feedback, participants performed long jumps with and without ear plugs (for similar designs, see Schaffert et al., 2020; Takeuchi, 1993) while wearing a portable eye-tracking system. All trials were additionally recorded by a digital camera to derive step characteristics from frame-by-frame analyses. Data were then compared between both conditions. According to previous findings on the impact of auditory feedback on motor performance (cf. Agostini et al., 2004; Castiello et al., 2010; Kennel et al., 2015; Schaffert et al., 2020), and in line with neurophysiological research (Crasta et al., 2018; Large & Snyder, 2009) supporting the notion that rhythmic auditory stimuli facilitate online error-corrections (Hossner et al., 2015), we hypothesized that the presence of concurrent, action-induced auditory feedback should affect and enhance all three performance measures. That is, participants were predicted to show: i) a prototypical gait pattern according to Lee et al. (1982) with increasing step lengths from fast and shorter steps in the acceleration phase to longer, adjusting steps in the zeroing-in phase; ii) higher gaze stability in terms of less switches between AOIs; and, given that more stable gaze patterns are associated with better and more stable motor performance (Klostermann et al., 2013; Klostermann & Moeinirad, 2020; Mann et al., 2007), iii) better jumping performance (i.e., farther jumped distances) in the presence of concurrent, action-induced auditory feedback.

5.2.1 Method

Participants

Twenty-five sport science students (M_{age} = 23.8 years, SD_{age} = 3.5 years; 14 male, 11 female) who were familiar with the long jump technique volunteered to take part in the experiment. All participants had completed a minimum of one athletic course as prescribed by the educational curriculum to ensure technical knowledge of the long jump. Nonetheless, they were not specialized in long jumping and therefore rather inexperienced long jumpers. Their mean jumped distance was 4.03 m (*SD* 0.68 m). All participants were in good health conditions (i.e., free from injuries, etc.) and had normal or corrected-to-normal vision and hearing.[5] The study design was approved by the ethics committee of the Faculty of Social and Behavioral Sciences of Friedrich Schiller University Jena. Participants provided written informed consent.

Apparatus

Data collection took place at an outdoor long jump facility at the local institute of sport science. A fixed digital camera (Sony Cyber-shot RX100 v, Sony Corporation, Tokyo, Japan; recording frequency: 60 fps) was used to record each trial for calculation of step characteristics and to perform a frame calibration upon participant's arrival. The camera was positioned on a tripod at a distance of 15 m from the middle of the run-up track and at a height of 1.80 m, covering a distance of 25 m (see Figure 5-1, for a similar experimental setup, see Hildebrandt & Cañal-Bruland, 2020). Gaze data acquisition was accomplished by the SMI ETG-2.6-1648-844 portable eye-tracking system (SensoMotoric Instruments, Teltow, Germany; sampling frequency: 60 Hz for each eye) including a smartphone recording unit (Samsung Galaxy Note 4, Samsung Group, Seoul, South Korea). Both data sources were temporally synchronized by an audio signal provided by a mini sound system (MusicMan TXX3549, Technaxx, Frankfurt am Main, Germany). For further analyses, video and eye-tracking data were transferred to a personal computer (Fujitsu

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[5] In terms of visual acuity, we relied on self-report as it appears to be common procedure within applied settings using portable eye-tracking systems to spare any vision testing (cf. Dicks et al., 2010; Mann et al., 2009; Martell & Vickers, 2004; Van Maarseveen et al., 2018). However, to ensure corrected vision, our experiments were only conducted with participants who were either not dependent on any optical aid or who were wearing contact lenses for vision correction. The same principle holds for hearing.

LIFEBOOK E Series, Fujitsu Technology Solutions GmbH, Tokyo, Japan) and consecutively edited with Matlab (Version R2019a, MathWorks, Inc., Natick, Massachusetts, United States of America), Microsoft Excel (Microsoft Corporation, Redmond, Washington, United States of America), R (Version 3.6.0, R Foundation, Vienna, Austria) and BeGaze (SensoMotoric Instruments, 2018, Version 3.7.60, Teltow, Germany). Participants wore the Moldex Spark Ear Plugs with a sound absorption capability of 35 dB (Moldex-Metric AG & Co. KG, Walddorfhäslach, Germany) in the auditory manipulation condition.

Procedure

Experimental preparation started upon each participant's arrival by calibrating the run-up track for later frame-by-frame analyses. For this purpose, distances from 0 m to 25 m from the take-off board in steps of 50 cm were marked on the run-up track with chalk spray. Afterwards, a laser device (Leica Disto X310, Leica Geosystems, St. Gallen, Switzerland) was moved along the chalk lines to verify the predefined distances relative to the take-off board. A ruler attached on the laser device (i.e., facing the camera) functioned as a calibration aid to mark the distances for the frame-by-frame video analyses.

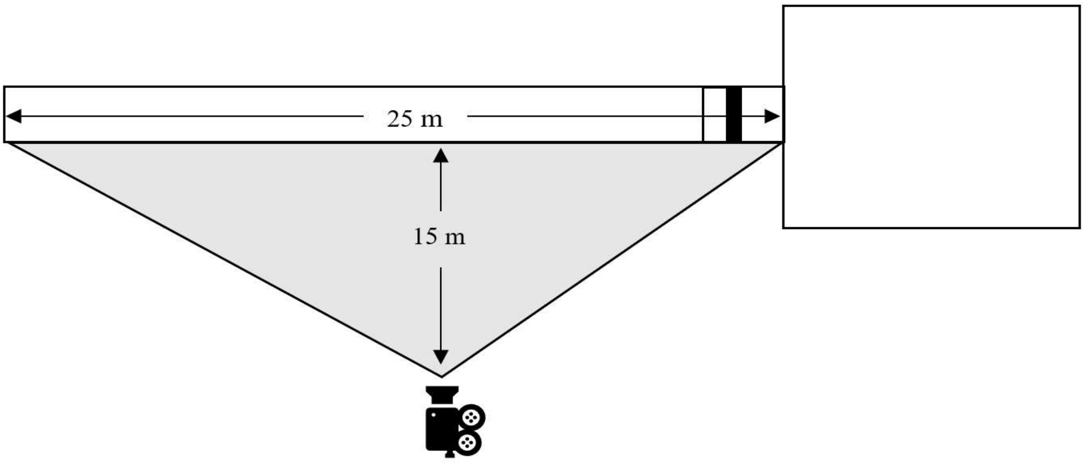

Figure 5-1. Schematic illustration of the experimental setup.

After completing a standardized warm-up procedure of 25 min (cf. Hildebrandt & Cañal-Bruland, 2020), participants performed three test trials to determine their individual run-up distance (range: 11.46–24.16 m). Then, the eye-tracking equipment including the SMI glasses and recording unit was attached to the participant using a chest strap. To ensure gaze tracking quality, a three-point calibration procedure was adopted using a poster horizontally displaying three circles in different colors with a diameter of 7 cm. The circles were set up in a triangular format and the center of each circle was presented in a contrasting color to the rest of the circle. Participants had to fixate the center of each circle subsequently without head movements. The calibration matrix was presented at eye height at a distance of approximately 1.50 m in accordance with the guidelines of the SMI-iView manual. Additionally, this distance is also supported by different studies (cf. Matthis et al., 2018; Matthis & Fajen, 2014), reporting that people consistently tend to look two steps ahead when walking over different terrains. Bearing in mind the investigation by Jasuja et al. (1997), indicating that the normal walking step length of a healthy person is about 73.6 cm, two steps would approximately equal a distance of 1.50 m. Therefore, our calibration distance might even represent participants' field of view while moving the whole body.

The experiment was conducted within a counterbalanced design, i.e., participants with uneven IDs (e.g., 1, 3, 5 etc.) first performed six jumps under normal conditions and subsequently six jumps with ear plugs, participants with even IDs (e.g., 2, 4, 6 etc.) performed their jumps in reversed order. This design was chosen to i) rule out order effects and ii) prevent participants from putting the ear plugs constantly in and out. Independent of condition, participants wore the portable eye-tracking glasses. Each trial started with an audio signal - a high frequent beep sound - to ensure temporal synchronization between both data sources and to indicate the beginning of the trial to the participants. Participants did not receive any instructions on where to focus their gaze prior to trial initiation. In case participants wore the ear plugs and did not register the audio signal, the experimenter signalized the beginning of a trial by a hand gesture ("thumbs up"). The validity of each trials' take-off position and the official jumped distances (i.e., distance from the take-off board) were assessed by the experimenter and an assistant. Participants were instructed to rest after each trial for 3-5 min before moving on to the next trial. If necessary, the three-point-calibration of the eye-tracking system was repeated in these rest breaks. At the end of the experiment, participants filled in a final questionnaire consisting of several demographic questions (e.g., age, gender, etc.) and experiment-related questions (e.g., long jump experience, training frequency, take-off foot, evaluation of their (auditory) impressions within the ear plug condition). The experiment took approximately 45 min to complete per participant.

Data analysis

We derived several gait-based and gaze-based measures from our experimental data. According to the two-phase model of the long jump run-up as suggested by Lee et al. (1982), we examined our variables separately for *acceleratio*n and *zeroing-in* and compared them between both conditions for a more fine-grained analysis.

Gait characteristics (i.e., step lengths, distances to the take-off board) were calculated through the identification of pixel positions for every calibrated distance in the frame-by-frame analyses in Matlab. The same procedure was applied for each trial to define the pixel positions for every footfall (i.e., distance between two successive foot touchdowns; Hay & Nohara, 1990) of the run-up. Pixel positions were subsequently entered into a Microsoft Excel spreadsheet before toe-to-board distances for every footfall were computed from calibration data via quadratic functions in R. With this procedure, it was possible to calculate step length as well as step and run-up duration. With respect to the maximum resolution of our camera setting (i.e., 1.5 cm per pixel), the mean standard error for distance calculation within this method was 0.03 m (cf. Berg et al., 1994; Hildebrandt & Cañal-Bruland, 2020). To identify the two phases of the long jump run-up, the standard deviation (SD) of toe-board distance for each step across participants' trials with and without ear plugs was computed as the step of maximum SD is said to mark the transition between acceleration and zeroing-in (cf. Hay & Koh, 1988). This individual step of maximum SD of toe-board distance for each participant was then used to divide each trial into two subsections. Gait parameters were calculated for each subsection (i.e., run-up phase) individually.

For our gaze characteristics, the eye-tracking files were first transferred into the BeGaze software. Due to our gait analyses, it was possible to assess total run-up duration for every trial by determining how many milliseconds after presentation of the audio signal participants initiated their run-up. Likewise, as we divided each trial into two subsections by means of the step of maximum SD of toe-board distance, we specified the individual phase durations of acceleration and zeroing-in. To ensure temporal synchronization, these time windows were then identified in the gaze videos. Using the semantic gaze mapping feature in BeGaze, four areas of interest (AOI; track, take-off board, sandpit, other) were defined. The fourth category ("other") accounted for all gaze behaviors that were not directed at any of the other AOI. AOI dwell times (in ms and %) were exported for each participant and each trial and were also considered separately for the phases of the run-up. According to the BeGaze manual, AOI dwell times are characterized as the sum of all dwell times for each visit of an AOI including all saccades and fixations inside the AOI. Additionally, participants' number of switches between AOIs were considered as a measure of gaze variability (cf. Baurès et al., 2015). Mean values for these variables were then calculated for each participant out of six trials according to the condition. For jumps without ear plugs 88.72% and for jumps with ear plugs 90.06% of participants' dwell times could be tracked successfully.[6] Data analyses were conducted using JASP 0.11.1 (JASP Team 2019, University of Amsterdam, Netherlands). First, to test whether the auditory manipulation had an impact on participants' gait behavior (i.e., step length) within the two phases of the run-up, we ran a 2 (condition: without ear plugs vs. with ear plugs) by 2 (phase: acceleration vs. zeroing-in) ANOVA. Second, we conducted another 2 (condition: without ear plugs vs. with ear plugs) by 2 (phase: acceleration vs. zeroing-in) by 4 (dwell times on AOIs: track, take-off board, sandpit, other) ANOVA to examine the influence of the auditory manipulation on participants' gaze behavior within the run-up phases. To further scrutinize whether wearing ear plugs affected participants' number of switches between AOIs as a measure of gaze variability, we ran another 2 (condition:

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[6] Gaze tracking ratios were automatically computed by BeGaze software and resemble the entirety of all gazes that could be successfully matched to an area of interest (AOI), i.e., cases in which pupil reflections were correctly detected. The remaining percentages reflect the amount of lost gaze data to to the high sensitivity of the eye-tracking system to environmental conditions (e.g., lighting) or person-related parameters (e.g., sweat).

without ear plugs vs. with ear plugs) by 2 (phase: acceleration vs. zeroing-in) ANOVA. Third, to examine whether the auditory manipulation of wearing ear plugs affected participants' jumped distance, we conducted a paired sample *t*-test.

In total, data of all 150 jumps without ear plugs (72.67% valid, 27.33% invalid[7]) as well as all 150 jumps with ear plugs (68.67% valid, 31.33% invalid) were included in the data analysis. Mean parameter values from each trial were calculated for each participant. The effect sizes for analyses of variance are reported as partial eta squared (η^2_p) and for *t*-tests as Cohen's d. Alpha was set at 0.05 for all statistical analyses.

5.2.2 Results

Gait Data

The first 2 (condition: without ear plugs vs. with ear plugs) by 2 (phase: acceleration vs. zeroing-in) ANOVA showed no significant main effect for condition on step length ($F(1, 24) = 0.76$, $p = .392$, $\eta^2_p = 0.03$). However, there was a significant main effect for phase ($F(1, 24) = 186.56$, $p < .001$, $\eta^2_p = 0.89$), indicating that step lengths differed significantly between acceleration and zeroing-in (see Figure 5-2). Additionally, there was a significant interaction between condition and phase ($F(1, 24) = 4.73$, $p = .04$, $\eta^2_p = 0.16$), revealing that the auditory manipulation differently affected participants' step lengths depending on the phase of the run-up. Participants displayed shorter step lengths in the acceleration phase with ear plugs ($M = 1.39$ m, $SD = 0.19$ m) than without ear plugs ($M = 1.45$ m, $SD = 0.21$ m), while their step lengths in the zeroing-in phase were minimally larger with ear plugs ($M = 1.77$ m, $SD = 0.20$ m) when compared to trials without ear plugs ($M = 1.76$ m, $SD = 0.15$ m). Figure 5-2A illustrates this relationship.

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[7] Trial invalidity indicates a crossing of the foul line, i.e., participants did not hit the take-off board properly. Invalid trials were included into data analyses in keeping with previous studies (cf. Bradshaw & Aisbett, 2006; Galloway & Connor, 1999; Hildebrandt & Cañal-Bruland, 2020; Scott et al., 1997; Theodorou & Skordilis, 2012) and to avoid data loss. Additional analyses confirmed for both Experiment 1 and Experiment 2 that none of our outcome measures was significantly affected by trial (in)validity. Likewise, there were no significant differences regarding trial (in)validity between conditions.

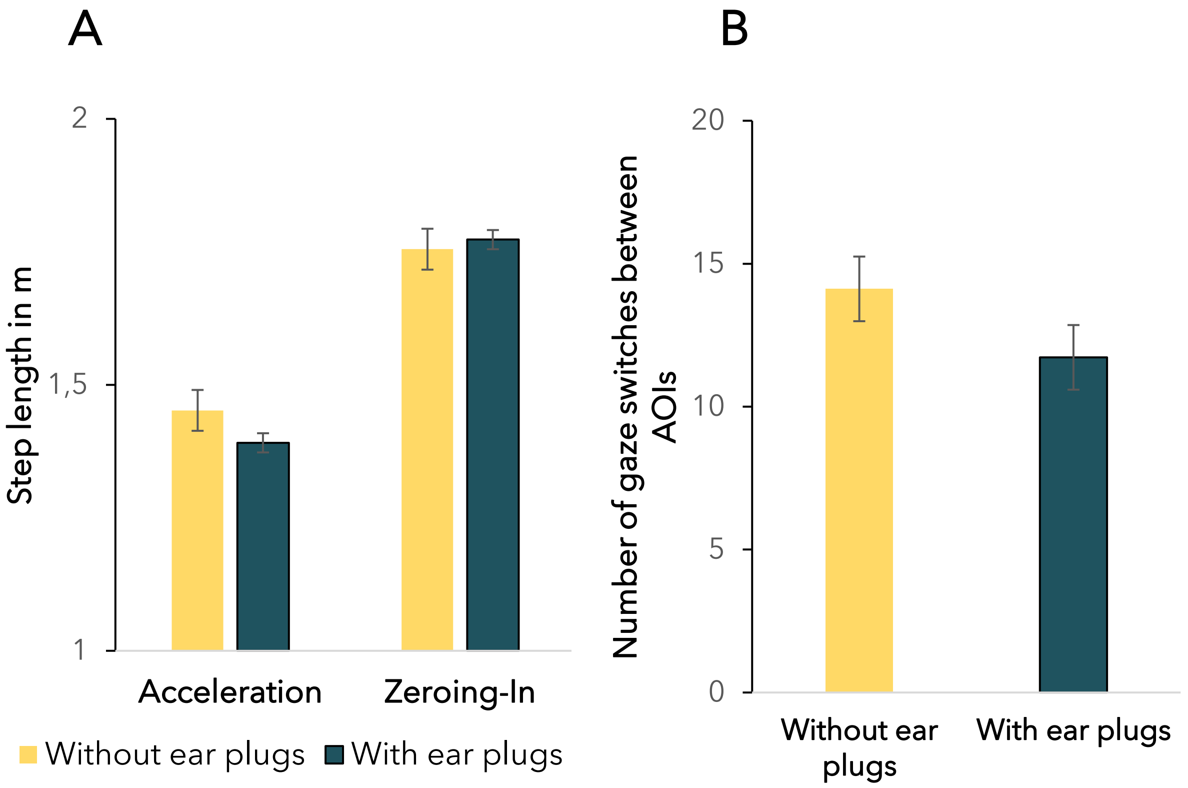

Figure 5-2. Mean step length in m for acceleration and zeroing-in (A) and mean number of gaze switches between the AOIs (B), each separated by condition. Error bars indicate 95% confidence intervals.

Gaze Data

Dwell times

The 2 (condition: without ear plugs vs. with ear plugs) by 2 (phase: acceleration vs. zeroing-in) by 4 (dwell times on AOIs: track, take-off board, sandpit, other) ANOVA showed no significant main effect for condition ($F(1, 24) = 0.24$, $p = .630$, $\eta^2_p = 0.01$), but a significant main effect for phase ($F(1, 24) = 16.75$, $p < .001$, $\eta^2_p = 0.41$), indicating that the distribution of dwell times differed significantly between both phases of the run-up ($M = 24.96\%$ per AOI ($SD = 0.08\%$ per AOI) for the acceleration phase; $M = 21.92\%$ per AOI ($SD = 7.23\%$ per AOI) for the zeroing-in phase) due to the unequal amounts of successfully tracked gaze data (i.e., tracking ratios) between acceleration and zeroing-in phase. Furthermore, there was a significant main effect for AOI ($F(1, 24) = 23.63$, $p < .001$, $\eta_p = 0.50$), illustrating that the mean dwell times differed significantly between AOIs (track, $M = 63.6\%$ ($SD = 25.8\%$); take- off board, $M = 6.22\%$ ($SD = 5.51\%$); sandpit, $M = 10.58\%$ ($SD = 7.78\%$); other, $M = 14.4\%$ ($SD = 22.88\%$)). The significant interaction between phase and AOI (*F*(1, 24) = 35.078, *p* < .001, η_p = 0.59) supports these findings across both phases of the run-up (acceleration: track, *M* = 72.99% (*SD* = 29.32%); take-off board, *M* = 4.42% (*SD* = 4.47%); sandpit, *M* = 4.7% (*SD* = 6.02%); other, *M* = 17.72% (*SD* = 26.97%); zeroing-in: track, *M* = 13.21% (*SD* = 11.57%); take-off board, *M* = 37.46% (*SD* = 27.19%); sandpit, *M* = 13.65% (*SD* =11.01%); other, *M* = 23.36% (*SD* = 18.94%)). Neither the two-way interactions between condition and phase (*F*(1, 24) = 0.26, *p* =.618, η_p = 0.01) and between condition and AOI (*F* (1, 24) = 0.48, *p* = .696, η_p = 0.02), nor the three-way interaction between condition, phase and AOI (*F*(1, 24) = 0.84, *p* = .475, η_p = 0.03) attained significance.

Gaze Switches

Finally, the 2 (condition: without ear plugs vs. with ear plugs) by 2 (phase: acceleration vs. zeroing-in) ANOVA showed a significant main effect for condition on participants' number of switches between AOIs (*F*(1, 24) = 4.31, *p* = .049, η^2_p = 0.15). This finding indicates that the mean number of switches between AOIs differed significantly between both auditory conditions and that participants switched less between AOIs in the ear plugs condition (*M* = 14.12 switches without ear plugs (*SD* = 9.38 switches); *M* = 11.72 switches with ear plugs (*SD* = 8.30 switches)). Figure 2B illustrates the corresponding descriptive values. However, there was neither a significant main effect for phase (*F*(1, 24) = 0.05, *p* = .820, η_p = 0.002) nor a significant interaction between condition and phase (*F*(1, 24) = 0.12, *p* = .733, η_p = 0.005).

Jumping performance

The paired sample *t*-test revealed no significant differences between jumps without ear plugs (*M* = 4.05 m, *SD* = 0.72 m) and jumps with ear plugs (*M* = 3.98 m, *SD* = 0.18 m; *Cohen's d* = 0.19, *p* = .365).

5.2.3 Discussion

Results of Experiment 1 indicate, first, that the presence vs. absence of auditory feedback during the long jump run-up influenced participants' step lengths depending on the phase of the run-up. That is, participants displayed shorter step lengths in the acceleration phase and longer step lengths in the zeroing-in phase in the absence (vs. presence) of auditory feedback. This is in contrast to what we expected, given that a prototypical long jump is characterized by a constant increase in step length with fast and short steps in the acceleration phase and long, adjusting steps in the zeroing-in phase (see Lee et al., 1982). In fact, our results show that participants' gait behavior was closer to the prototypical (ideal) run-up pattern when no auditory feedback was present. It hence seems that the absence rather than the presence of auditory feedback facilitated the execution of functional gait patterns. However, even if the ear plugs effectively suppressed the surrounding noises and "objective" auditory information at the long jump facility, it cannot be ruled out that wearing the ear plugs led participants to rely more on "subjective" tactile and proprioceptive information of the toe-track contact via bone conduction or structure-borne sound respectively and that this tactile information likewise induced a perceptual impression of rhythmicity. Regarding participants' gaze behavior, our analyses revealed a more variable gaze pattern (i.e., more gaze switches between AOIs) in the presence of auditory feedback, and a more stable gaze pattern (i.e., less gaze switches between AOIs) when auditory feedback was absent. At first sight, and similar to our results for the gait pattern analysis, this finding seems to be counterintuitive as we hypothesized that the present auditory feedback would lead to a higher gaze stability in terms of less gaze switches and a beneficial effect on motor performance (Klostermann et al., 2013; Klostermann & Moeinirad, 2020; Mann et al., 2007). However, there is empirical evidence supporting the idea that the deprivation of one sensory modality might actually reinforce other sensory modalities. For instance, a study by Araneda et al. (2016) revealed that blind persons developed superior olfactory abilities due to cortical reorganization processes. Similarly, Brodoehl et al. (2015) demonstrated that participants displayed a better somatosensory perception of objects with their eyes closed as the brain probably alternates to a different processing mode. This explanation is in agreement with our empirical findings for both the gaze and gait patterns, showing that the auditory deprivation resulted in a higher gaze stability (i.e., less switches between AOIs) and a more prototypical (ideal) run-up pattern. Finally, despite its impact on the run-up pattern and gaze behavior, and in contrast to previous studies (e.g., Schaffert et al., 2020), the auditory manipulation did not affect participants' jumped distances in Experiment 1. Taken together, the results of Experiment 1 indicate that the presence vs. absence of auditory feedback affected both gait as well as gaze patterns in long jumping. Yet, contrary to the original hypotheses, the absence (rather than the presence) enhanced gait and gaze characteristics. This may potentially be explained by research indicating that the deprivation of one sensory modality might reinforce or enhance the processing of other sensory modalities. Given that our findings are in partial conflict with previous studies (e.g., Schaffert et al., 2020), we needed to rule out that and examine whether our findings may be a result of having applied a different paradigm or task (i.e., long jumping). We therefore decided to run a second experiment and aimed to partially replicate Kennel et al. (2015; hurdle jumping) by applying their manipulation, that is, delayed vs. concurrent auditory feedback within our long jumping task.

5.3 Experiment 2

To rule out that the effects found in Experiment 1 may be a mere consequence of using a different task, we aimed at partially replicating Kennel et al. (2015) by examining the impact of delayed vs. concurrent auditory feedback on long jumping performance in terms of gait (i.e., step length) and gaze behavior (i.e., dwell times on AOIs, number of switches between AOIs) as well as jumped distance. Based on their findings with respect to a significant decrease in participants' movement performance and movement stability, Kennel et al. (2015) inferred that auditory information seems to be crucial for error detection during motor tasks due to the online effect of perceptual processes on action (cf. Schütz-Bosbach & Prinz, 2007). In addition, they argued that modified (i.e., delayed) auditory feedback negatively affects error-correction processes during movement execution resulting in poorer performance. To verify whether these effects are also observable not only within another complex motor task but also on other dimensions apart from performance such as gaze behavior, in Experiment 2 participants performed long jumps with and without delayed auditory feedback while wearing a portable eye-tracking system. All trials were additionally recorded by a digital camera to derive step characteristics based on frame-by-frame analyses.

Data were then compared between both conditions. In keeping with our original hypotheses (see Experiment 1) and the findings by Kennel et al. (2015), we expected the veridical (i.e., not manipulated) auditory feedback to be superior to delayed auditory feedback in terms of a facilitating effect on participants’ gait (i.e., a prototypical gait pattern; Lee et al., 1982), gaze (i.e., higher gaze stability in terms of less switches between AOIs) and jumping performance (i.e., farther jumped distances).

5.3.1 Method

Participants

Eighteen sport science students (M_{age} 23.28 years, SD_{age} 2.52 years; 9 male, 9 female) who were familiar with the long jump technique volunteered to take part in the experiment. As in the first experiment, participants had completed a minimum of one athletic course as prescribed by the educational curriculum to ensure technical knowledge of the long jump. It follows that similar to Experiment 1, they were not specialized in long jumping and are therefore characterized as rather inexperienced long jumpers. Their mean jumped distance was 4.15 m (*SD* 0.58 m). All participants were again in good health conditions (i.e., free from injuries etc.) and had normal or corrected-to-normal vision and hearing.[5] The study design was approved by the ethics committee of the Faculty of Social and Behavioral Sciences of Friedrich Schiller University Jena. Participants provided written informed consent.

Apparatus

The experiment took place at an indoor long jump facility. The same fixed digital camera as in Experiment 1 was positioned on a tripod at a distance of 15 m from the take-off board and at a height of 1.80 m, resulting in a viewing angle of approximately 45° and a covered distance of 40 m. The rest of the apparatus was mostly identical to Experiment 1, except for the auditory feedback which was provided through an online feedback system to record participants' step movement sounds. These sounds were presented to the participants through on-ear headphones (Beats Solo 3, Beats Electronics, LLC, Santa Monica, California, United States of America). Similar to Kennel et al. (2015), we chose on-ear headphones as pilot tests confirmed a size-adjustable and tight fit on the head without falling off. The feedback system included a condenser microphone (C 417 L, AKG, Vienna, Austria) with an omnidirectional polar pattern (sensitivity at 1 kHz: 10 mV/Pa (−40 dBV re 1 V/Pa) and maximum sound pressure level (SPL) for 1%/3% THD: 118/126 dB SPL), a battery supply unit (B 29 L, AKG, Vienna, Austria), an audio delay converter (DCT-18, SpeaKa Professional, Hirschau, Germany) and a headphone amplifier (Hardwired In-Ear Body Pack, Fischer Amps, Osterburken, Germany). The technical components were connected by high qualitative XLR or Cinch connectors. The complete array was attached to an individually adjustable climbing harness worn around the hips. The total weight of the technical equipment was 1.4 kg. For a more detailed description of the setup, see Kennel et al. (2015).

Procedure

The experimental procedure was the same as in Experiment 1, except for the manipulation. While participants received their conventional step sounds within the concurrent condition, in the auditory manipulation condition, participants' step sounds were presented with a delay. As we aimed for a conceptual replication of Kennel et al. (2015) by using the same online feedback apparatus, we also opted for the same delay interval of 180 ms. Based on the results of an investigation by Menzer et al. (2010) in which the authors examined the impact of footstep sounds with different delay intervals on the sense of agency, Kennel et al. (2015) inferred that a delay of 180 ms seemed suitable for the examination of delayed auditory feedback on hurdling performance as i) footstep sounds with a delay of 180 ms are still considered self-generated and ii) the delay was technically implementable with respect to the equipment. Independent of condition, participants always wore the portable eye-tracking glasses. The experiment took approximately 60 min to complete per participant.

Data analysis

Data processing and statistical analyses were the same as in Experiment 1 with gaze tracking ratios[6] of 95.04% for jumps without delay and 92.71% for jumps with delay. Similar to Experiment 1, the maximum camera resolution was 1.6 cm per pixel resulting in a mean standard error for distance calculation of 0.03 m (cf. Berg et al., 1994; Hildebrandt & Cañal-Bruland, 2020). First, to test whether the auditory manipulation had an impact on participants' gait behavior (i.e., step length) within the two phases of the run-up, we ran a 2 (condition: without delay vs. with delay) by 2 (phase: acceleration vs. zeroing-in) ANOVA. Second, we conducted another 2 (condition: without delay vs. with delay) by 2 (phase: acceleration vs. zeroing-in) by 4 (dwell times on AOIs: track, take-off board, sandpit, other) ANOVA to examine the influence of the auditory manipulation on participants' gaze behavior within the run-up phases. To further examine whether the delayed auditory feedback affected participants' number of switches between AOIs as a measure of gaze variability, we ran an additional 2 (condition: without delay vs. with delay) by 2 (phase: acceleration vs. zeroing-in) ANOVA. Third, to finally analyze whether the auditory manipulation of delayed auditory feedback affected participants' jumped distance, we conducted a paired sample t-test.

In total, data of all 108 jumps without delayed feedback (69.44% valid, 30.56% invalid[7]) as well as all 108 jumps with delayed auditory feedback (60.18% valid; 39.82% invalid) were included in the data analysis. Mean parameter values from each trial were calculated for each participant. The effect sizes for analyses of variance are reported as partial eta squared (η_p^2) and for t-tests as Cohen's d. Alpha was set at 0.05 for all statistical analyses.

5.3.2. Results

Gait Data

The first 2 (condition: without delay vs. with delay) by 2 (phase: acceleration vs. zeroing-in) ANOVA revealed a significant main effect for condition on step length ($F(1, 17) = 7.22$, $p = .016$, $\eta_p^2 = 0.31$), indicating that participants' displayed shorter overall step lengths with delayed auditory feedback ($M = 1.54$ m, $SD = 0.22$ m) than without auditory delay ($M = 1.60$ m, $SD = 0.16$ m; see Figure 5-3A). The main effect for phase was also significant ($F(1, 17) = 60.884$, $p < .001$, $\eta_p^2 = 0.79$), step lengths in the acceleration phase were significantly shorter ($M = 1.40$ m, $SD = 0.28$ m) than step lengths in the zeroing-in phase ($M = 1.71$ m, $SD = 0.17$ m). However, there was no significant interaction between condition and phase ($F(1, 17) = 2.57$, $p = .128$, $\eta_p^2 = 0.139$).

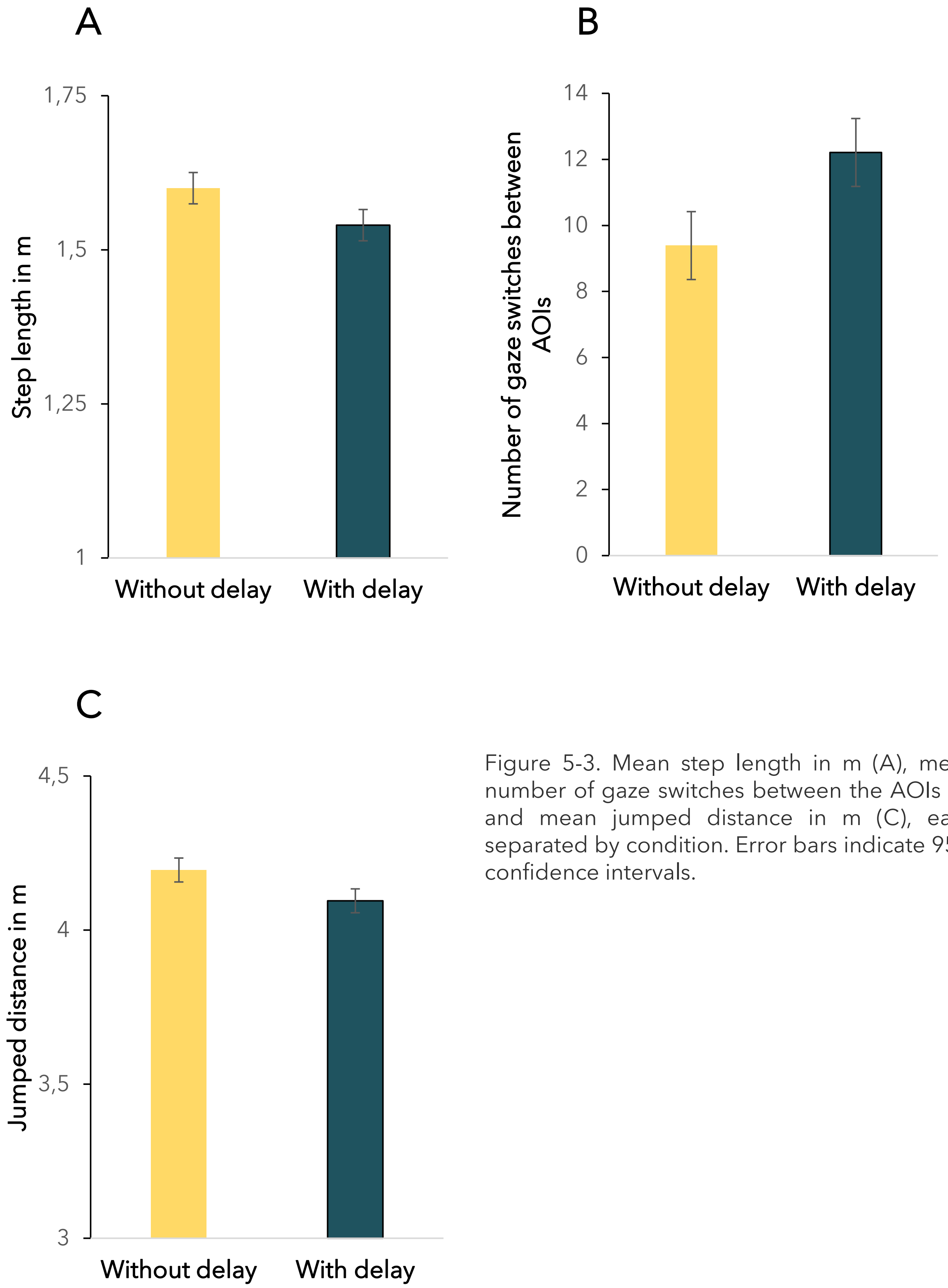

Figure 5-3. Mean step length in m (A), mean number of gaze switches between the AOIs (B) and mean jumped distance in m (C), each separated by condition. Error bars indicate 95% confidence intervals.

Gaze Data

Dwell times

The 2 (condition: without delay vs. with delay) by 2 (phase: acceleration vs. zeroing-in) by 4 (dwell times on AOIs: track, take-off board, sandpit, other) ANOVA yielded neither a significant main effect for condition ($F(1, 17) = 2.90$, $p = .107$, $\eta^2_p = 0.146$) nor for phase ($F(1, 17) = 0.005$, $p = .946$, $\eta^2_p < 0.001$). However, there was a significant main effect for AOI ($F(1, 17) = 49.05$, $p < .001$, $\eta^2_p = 0.743$), indicating that the mean dwell times differed significantly between AOIs (track, $M = 61.13\%$ ($SD = 22\%$); take-off board, $M = 8.01\%$ ($SD = 5.57\%$); sandpit, $M = 16.35\%$ ($SD = 12.54\%$); other, $M = 6.92\%$ ($SD = 8.59\%$)). The significant interaction between phase and AOI ($F(1, 17) = 21.51$, $p < .001$, $\eta_p = 0.56$) supports these findings across both phases of the run-up (acceleration: track, $M = 74.53\%$ ($SD = 22.57\%$); take-off board, $M = 4.54$ ($SD = 6.75\%$); sandpit, $M = 5.61\%$ ($SD = 8.68\%$); other, $M = 7.56\%$ ($SD = 8.84\%$); zeroing-in: track, $M = 47.74\%$ ($SD = 29.38\%$); take-off board, $M = 11.47\%$ ($SD = 8.86\%$); sandpit, $M = 27.1\%$ ($SD = 17.98\%$); other, $M = 6.28\%$ ($SD = 9.42\%$)). Neither the two-way interactions between condition and phase ($F(1, 17) = 1.44$, $p = .247$, $\eta_p = 0.08$) and condition and AOI ($F(1, 17) = 0.70$, $p = .559$, $\eta_p = 0.04$) nor the three-way interaction between condition, phase and AOI ($F(1, 17) = 1.44$, $p = .243$, $\eta_p = 0.08$) reached significance.

Gaze Switches

Finally, the 2 (condition: without delay vs. with delay) by 2 (phase: acceleration vs. zeroing-in) ANOVA revealed a significant main effect for condition on participants' number of switches between AOIs ($F(1, 17) = 7.20$, $p = .016$, $\eta^2_p = 0.30$), indicating that participants switched more between AOIs in the delay condition ($M = 12.21$ switches, $SD = 8.77$ switches) than in the no delay condition ($M = 9.39$ switches, $SD = 6.10$ switches; see Figure 5-3B). However, there was neither a significant main effect for phase ($F(1, 17) = 3.56$, $p = .076$, $\eta_p = 0.173$) nor a significant interaction between condition and phase ($F(1, 17) = 0.17$, $p = .686$, $\eta_p = 0.010$).

Jumping performance

The paired sample t-test revealed a significant effect of the auditory manipulation on jumped distance (Cohen's d = 0.60, p = .022), indicating that participants jumped further with concurrent auditory feedback (M = 4.20 m, SD = 0.61 m) than with delayed auditory feedback (M = 4.10 m, SD = 0.56 m; see Figure 5-3C).

5.3.3 Discussion

In agreement with our hypotheses, results of Experiment 2 revealed that the auditory manipulation (i.e., delaying auditory feedback by 180 ms) led to significant deteriorations in all three measures. First, participants showed a more prototypical (ideal) gait pattern (Lee et al., 1982) in the concurrent auditory feedback condition than in the delayed auditory feedback condition. More specifically, when auditory feedback was delayed, participants displayed significantly shorter step lengths across both phases of the run-up. This finding is in agreement with the effects of the auditory manipulation reported in Kennel et al. (2015) in hurdle jumping and might even support the alternation of velocity perception caused by auditory feedback as introduced by Effenberg and Schmitz (2018). As fast and short steps typically occur in the acceleration phase to build up adequate velocity, the delayed auditory feedback might have led participants to the impression of a slow run-up resulting in overall shorter (and maybe even faster) steps. Second, regarding participants' gaze behavior, our results confirmed a more stable gaze pattern when the auditory feedback was concurrent than when it was delayed. More specifically, in the delayed feedback condition, participants showed more switches between AOIs, indicating that the delayed auditory feedback resulted in a more variable gaze pattern. It hence seems that the delayed auditory feedback perturbed participants' gaze behavior and was detrimental to realizing their habitual and more functional gaze patterns displayed in the concurrent auditory feedback condition. According to the elaborations by Chase et al. (1961), delayed auditory feedback might have led to an impaired information integration from different sensory modalities which affected participants' gaze behavior. Thus, we argue that the less stable gaze patterns in the delay condition might reflect a dysfunctional (over)compensation of the visual system for the altered auditory feedback and the deviations from the prototypical gait pattern. Given that more stable gaze patterns are associated with better motor performance (Klostermann et al., 2013; Klostermann & Moeinirad, 2020; Mann et al., 2007), this effect of auditory feedback on gaze patterns (cf. Shams et al., 2004), may also explain the impact of the auditory manipulation on performance. That is, third, in keeping with the findings by Kennel et al. (2015), participants showed better performance outcomes (i.e., jumped further) with concurrent than with delayed auditory feedback. We argue that delayed auditory feedback may have impaired participants' online error-correction (cf. Hossner et al., 2015), as evidenced by maladaptive gaze patterns and dysfunctional deviations from participants' prototypical run-up gait patterns.

5.4 General discussion

There is a growing body of literature focusing on the effects of auditory information on perceptual processes and motor performance (for recent reviews, see Schaffert et al., 2019; Stanton & Spence, 2020). Previous studies have revealed that convergent auditory feedback led to facilitatory effects on motor execution in simple motor tasks such as grasping (Castiello et al., 2010) and writing (Danna et al., 2015) as well as in complex motor tasks such as hammer throwing (Agostini et al., 2004). Further, incongruent auditory feedback decreased motor performance in different contexts such as piano playing (Drost et al., 2005) and hurdle jumping (Kennel et al., 2015). Finally, absent auditory feedback negatively influenced motor performance in a complex task such as rowing (Schaffert et al., 2020).

While previous research has predominantly focused on measures of performance outcome (cf. Agostini et al., 2004) and motor control parameters (Kennel et al., 2015; Schaffert et al., 2020), the aim of the current study was to add to this literature by examining gaze characteristics in long jumping (Hildebrandt & Cañal-Bruland, 2020) additionally to gait characteristics (e.g., Bradshaw & Aisbett, 2006; Hay, 1988; Scott et al., 1997) and performance outcomes. While Experiment 1 was designed to examine whether and if so how the presence (vs. absence) of concurrent auditory feedback (i.e., action-induced sounds) affects gait, gaze and outcome performance, Experiment 2 aimed at testing the impact of concurrent vs. delayed auditory feedback (Kennel et al., 2015) on these measures.

The results of the current study provided further evidence that auditory information in terms of i) present vs. absent and ii) concurrent vs. delayed action-induced auditory feedback play a crucial role in the coordination of complex, rhythmical motor tasks. While our first experiment revealed a facilitatory effect of absent (rather than present) auditory feedback on participants' gait patterns and gaze behavior, our second experiment indicated that concurrent auditory feedback was superior to delayed auditory feedback concerning all three performance parameters.

Given that the auditory deprivation in Experiment 1 did not affect our outcome measures as hypothesized, our empirical findings may support the notion that both our auditory manipulations underlie different mechanisms. In this regard, Chase et al. (1961) hypothesized that the deprivation of one sensory modality leads to the ignorance of this then *useless* feedback channel and a narrowing of the focus on other sensory sources. Regarding the results of Experiment 1, participants presumably paid more attention to the visual (i.e., visible in more stable gaze patterns) and the tactile (i.e., "subjective" tactile feedback of heel strikes and bone conduction) modality. This phenomenon of interdependency between feedback channels was also observed in deaf participants (Finney et al., 2003) and participants with synaesthesia (Grossenbacher & Lovelace, 2001). Additionally, Araneda et al. (2016) as well as Brodoehl et al. (2015) provided evidence that the deprivation of one sensory modality can "boost" other sensory modalities. If true, participants' higher gaze stability in the absence of auditory feedback might have been the result of visual enhancement caused by auditory deprivation and the same logic might apply to participants' gait behavior. Notably, this explanation seems to be supported also by participants' subjective impressions as reported in a final exit questionnaire, in which several participants (i.e., 17 out of 25 participants) noted an enhanced sense of focus and less distraction in the auditory deprivation condition (i.e., when wearing ear plugs), similar to the athletes in study by Schaffert et al. (2020). Together, this may also explain why the presence of auditory feedback in Experiment 1 did not result in better motor performance (i.e., farther jumped distances). To conclude, we argue that the auditory deprivation was compensated by other sensory modalities in a *functional* way, i.e., the auditory feedback was not explicitly necessary for the implementation of stable gaze and gait patterns during the run-up as the visual and tactile information seemed to be sufficient for successful task execution.

In contrast, following the suggestions by Chase et al. (1961), the delayed auditory feedback in Experiment 2 might have caused severe changes of the sensory event due to a faulty error-correction process (cf. Hossner et al., 2015). Based on the assumption that normal (i.e., naturally occurring) auditory feedback emerges simultaneously with motor action, one corollary might be that the delayed auditory feedback within our second experiment led to perturbations and an impaired information integration from different sensory modalities. Consequently, the temporal course of the motor action may not have been represented correctly (i.e., erroneous updating process of the internal model, cf. Wolpert & Ghahramani, 2000) and resulted in a perturbed motor routine (i.e., deviations from the prototypical run-up pattern, decreased jumped distance; cf. Kennel et al., 2015). With respect to the less stable gaze patterns in the auditory delay condition and given that more stable gaze patterns are associated with better motor performance (Klostermann et al., 2013; Klostermann & Moeinirad, 2020; Mann et al., 2007), we argue that the visual system might have (over)compensated for the impaired auditory feedback and the deviations from the motor routine in a *non-functional* way. That is, the visual modality potentially aimed at leveling out the delayed auditory feedback by implementing additional gaze shifts to reduce response uncertainty (cf. Castiello et al., 2010; Desmurget & Grafton, 2000). However, the changes in participants' gait patterns as well as the decreased motor performance seem to indicate that the increased gaze variability was not beneficial to overcome the consequences of the delayed auditory feedback. This interpretation, similar to Experiment 1, seems to be supported by our participants' subjective experiences as reported in a final exit questionnaire as several participants (i.e., 10 out of 18 participants) mentioned that the delayed auditory feedback led to significant distractions and irritations.

Alternatively, our findings might compliment the premises of the *modality appropriateness hypothesis* (Choe et al., 1975) which suggests that the modality that is most relevant to solve a certain task dominates task execution. Consequently, our findings might indicate that the execution of the long jump is rather visually than auditorily dominated as the auditory deprivation in Experiment 1 did not lead to any deteriorations, while the delayed auditory feedback in Experiment 2 significantly affected participants' gaze which in turn led to changes in motor behavior.

In the remainder of the discussion, we aim at elaborating on i) participant characteristics, ii) experimental facilities and iii) practical implications of our findings. First, our sample consistently included sport science students who – although recreationally active – obviously differed from elite long jumpers in terms of training frequency, experience (e.g., in intentionally hearing and using auditory feedback from footstep sounds) and motor performance capacities (i.e., jumped distances). For this reason, we cannot rule out that a replication of both experiments with an expert sample would reveal different effects. Particularly in terms of gaze behavior, current research suggested that expert athletes display higher gaze stability (i.e., less gaze shifts) than novice athletes (for recent overviews, see Brams et al., 2019; Mann et al., 2007). However, given that we applied a within-subject design as concerns our main manipulations in Experiment 1 (present vs. absent auditory feedback) and Experiment 2 (concurrent vs. delayed auditory feedback), we would expect these effects to generalize to other skill levels including experts, too. Clearly, future research is necessary to test this assumption.

Second, the differences of the long jump facilities used within the current study have to be addressed. Both facilities, outdoor as well as indoor, were similarly equipped with a tartan track. However, acoustics differed naturally between indoor and outdoor, for instance, in terms of noise and echoing. Even if the effects of auditory information may be omnipresent and therefore independent from different facilities, future studies would be well-advised to use noise-reduced facilities for the optimal implementation of auditory manipulations aiming at participants' step sounds.

Third, although further research is required to corroborate the present findings, the current study underpins the importance of auditory feedback for action execution which might also bear possible applications for training purposes, be it in sports or clinical settings. In this context, Stanton and Spence (2020) recently reviewed and discussed research providing evidence for the beneficial effects of movement sonification interventions (Dyer et al., 2017; Effenberg, 2005; Effenberg et al., 2016). In addition, to sport-related research, Stanton and Spence (2020) as well as Schaffert et al. (2019) also reported growing evidence from clinical research showing that auditory feedback, especially rhythmic auditory stimulation (RAS), seems to facilitate motor rehabilitation processes in patients with Parkinson's disease (cf. Hausdorff et al., 2007; Lim et al., 2005; Nieuwboer et al., 2007; Nombela et al., 2013; Rochester et al., 2010), stroke (cf. Thaut & Abiru, 2010; Yoo & Kim, 2016) or multiple sclerosis (cf. Conklyn et al., 2010; Shahraki et al., 2017).

Taken together, these findings once again emphasize the promising potential of auditory feedback for motor performance that needs to be exploited in further research.

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CHAPTER 6

MODALITY APPROPRIATENESS IN MOTOR RHYTHM REPRODUCTION

6 STUDY 3: AUDITORY PERCEPTION DOMINATES IN MOTOR RHYTHM REPRODUCTION

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Abstract

It is commonly agreed that vision is more sensitive to spatial information, while the auditory system is more sensitive to temporal information. When both visual and auditory information are available simultaneously, the modality appropriateness hypothesis (MAH) predicts that – depending on the task – the most appropriate (i.e., reliable) modality dominates perception. However, previous research scrutinizing the premises of the MAH mainly applied paradigms in which different sensory inputs provided *discrepant* information, however, the current study aimed at investigating the MAH when multimodal information was provided in a non-discrepant (i.e., concordant) and simultaneous manner. To this end, participants performed a temporal rhythm reproduction task for which – as is well known – the auditory modality is the most appropriate. Three experimental conditions were included: an auditory condition (i.e., beeps), a visual condition (i.e., flashing dots) and an audiovisual condition (i.e., beeps and dots simultaneously). Moreover, two distinctly complex types (i.e., constant and variable) of interstimulus-intervals (ISIs) were implemented. In line with the MAH, results revealed higher accuracy and lower variability in the auditory condition for both constant and variable ISIs when compared to the visual condition. More importantly, there were no differences between the auditory and the audiovisual condition across both ISI types. This indicates that the auditory modality seemingly dominated multimodal perception in the rhythm reproduction task, whereas the visual modality was disregarded and hence did not add to rhythm reproduction performance.

Keywords: Multisensory integration; Perception/action; Temporal processing; Modality appropriateness hypothesis; Rhythm reproduction

6.1 Introduction

Considering the variety of sensory inputs from the environment (Calvert et al., 1998), perception is by nature a multisensory process (Auvray & Spence, 2008; Calvert et al., 2004; Driver & Spence, 2000). For instance, when crossing a frequented street, pedestrians have to localize approaching vehicles by integrating available visual information (e.g., headlights) as well as auditory signals (e.g., horns or sirens) to generate a veridical and precise representation of the environmental circumstances (Spence, 2011) and to reduce perceptual ambiguity (Calvert et al., 1998). Certainly, this principle does not only apply to daily situations but also to more complex contexts involving time pressure, such as fast ball sports. For example, tennis players do not only rely on visual information from their opponents' movements and ball flight to anticipate the ball's trajectory but also derive information from the sound emanating from racquet-ball-contact (e.g., Cañal-Bruland et al., 2018) or an opponent's grunt (e.g., Müller et al., 2019).

Given that different sensory inputs are processed with high spatial and temporal coincidence (cf. Bedford, 2001; van Wassenhove et al., 2007), observers tend to attribute stimuli from different modalities to the same event resulting in the so-called *unity assumption* (cf. Jackson, 1953; Welch & Warren, 1980). However, an observer's assumption of unity does not necessarily imply that stimuli from different sensory sources contribute to perception to an equal extent. Bayesian approaches (see e.g., Körding et al., 2007; Körding & Wolpert, 2004), for instance, promote the fundamental idea that stimuli from different sensory modalities are weighted according to their informational value within a certain task. In addition, there are a plethora of studies suggesting that different sensory modalities interact and may even interfere with each other (for an overview, see Shimojo & Shams, 2001). In particular, there is evidence that the perceived intensity of a stimulus in one sensory modality is modulated by the simultaneous presentation of a second stimulus in another sensory modality (Sanabria et al., 2007; Shipley, 1964) – a phenomenon referred to as *intersensory bias* (Lukas et al., 2014; Welch & Warren, 1980). Following Welch and Warren (1980), the strength of intersensory bias is defined by structural factors (e.g., spatiotemporal discrepancy or coincidence) and cognitive factors (e.g., awareness on intersensory discrepancies, assumption of unity, compelling [i.e., stimulating] features of the situation).

Welch and Warren (1980) proposed that intersensory bias emerges because the perceptual system attempts to offer a percept that is most convenient for successfully solving the task at hand, implying that some modalities seem to be more suitable for certain task dimensions than others. In this regard, previous research predominantly focused on the visual modality (see e.g., Hutmacher, 2019) revealing an exceptionally robust bias of vision over audition, for instance, in terms of stimulus localization (Alais & Burr, 2004; Howard & Templeton, 1966; Lukas et al., 2014; Stratton, 1897) or speech perception (McGurk & MacDonald, 1976). According to Shimojo and Shams (2001), this strong effect supports the common assumption that human perception is first and foremost dominated by the visual modality. Despite this claim for the dominance of the visual modality, there is growing evidence that vision can also be dominated and altered by the auditory modality. Especially within the temporal domain, auditory stimuli were shown to dominate over visual stimuli in terms of judging interval duration and stimulus frequency (Burr et al., 2009; Gebhard & Mowbray, 1959; Recanzone, 2003; Shipley, 1964; Welch et al., 1986). Moreover, auditory information can also modify aspects of vision as sound signals have been shown to affect the perceived duration (Walker & Scott, 1981), stimulus intensity (Stein et al., 1996), and timing of a visual stimulus (Aschersleben & Bertelson, 2003; Fendrich & Corballis, 2001; Morein-Zamir et al., 2003; Parise & Spence, 2008; Shams et al., 2000) as well as manual interception (Tolentino-Castro et al., 2022). Additionally, auditory input can either increase or decrease visual temporal resolution (Shimojo et al., 2001) and alter the perceptual interpretation of an ambiguous (Sekuler et al., 1997) or non-ambiguous visual event (Shams et al., 2000; Zampini & Spence, 2004).

By now, it is commonly agreed that the visual system has a higher resolution in spatial tasks whereas the auditory system is more sensitive in temporal tasks (Näätänen & Winkler, 1999; O’ Connor & Hermelin, 1972; Recanzone, 2003;

Recanzone, 2009; Shimojo & Shams, 2001; Sandhu & Dyson, 2012; Spence & Squire, 2003; Welch & Warren, 1980; Welch et al., 1986). A commonly proposed explanation for these modality-specific preferences is offered by the *modality appropriateness hypothesis (MAH)* which is based on the notion that the sensory modalities, although each capable of various functions, are particularly specified to process information within appropriate dimensions (Freides, 1974; Lukas et al., 2014; O'Connor & Hermelin, 1972). In addition, the MAH is advocating the idea that the most appropriate (i.e., sensitive or reliable) modality will dominate perception within a multimodal task setting (Andersen et al., 2005; Matuz et al., 2019; Shimojo & Shams, 2001; Wada et al., 2003; Welch & Warren, 1980). According to Andersen et al. (2005) as well as Welch and Warren (1980), the appropriateness of a sensory modality is closely intertwined with attentional processes as human perception is proficient to estimate the relative reliability of different sensory sources and to purposefully direct attention towards the most reliable modality. The alignment of attention and, consequently, the processing of different sensory inputs due to the level of appropriateness are depending on stimulus characteristics (i.e., temporal, or spatial character, intensity, movement, salience, shape, size, orientation, texture; Shimojo & Shams, 2001; Welch & Warren, 1980) and task demands (e.g., whether it requires spatial or temporal processing; Lukas et al., 2014). Additionally, Welch and Warren (1980) reported that the more (temporally or spatially) complex a certain task, the more dominant the appropriate sensory modality will be.

While previous studies evaluating the premises of the MAH mainly used crossmodal switching tasks in which different sensory inputs provided *discrepant* information (see e.g., Lukas et al., 2010; Lukas et al., 2014; Matuz et al., 2019; Sandhu & Dyson, 2012), however, it remains to be determined whether the *less* appropriate modality may or may not significantly add to successfully solving a task in a multimodal context for which i) the most appropriate modality is known and ii) all modalities provide *non-discrepant* information. In other words: considering that different sensory inputs are not necessarily processed to the same extent although attributed to the same event (see e.g., Körding et al., 2007; Körding & Wolpert, 2004), and that task demands such as complexity seem to be of crucial importance to specify the *appropriateness* of sensory information from various modalities (see Welch & Warren, 1980), it is still an open question whether participants would benefit from additional and hence multimodal stimulation (as opposed to unimodal stimulation) if the task-dependent most appropriate modality was already addressed.

To examine this question and be able to compare unimodal vs. multimodal processing (Welch & Warren, 1980), it is mandatory to first identify a task for which the most appropriate or reliable modality is known. Previous research, for instance, revealed a particularly distinguished bias towards the auditory modality for rhythm reproduction tasks in which participants were instructed to reproduce visual or auditory rhythmical patterns as temporally precisely as possible. With respect to the higher sensitivity of the auditory system to temporal information (cf. Loeffler et al., 2018; O'Connor & Hermelin, 1972; Recanzone, 2009; Sandhu & Dyson, 2012), this task has been identified to be favorably solved within the auditory modality as participants' performance was significantly better when the rhythmical patterns were presented auditorily (cf. Chen et al., 2002; Hove et al., 2013; Glenberg & Jona, 1991; Kolers & Brewster, 1985; Gault & Goodfellow, 1938; Patel et al., 2005; Repp & Penel, 2004). For this reason, in the current study we chose to modify the rhythm reproduction task which has been applied by Sarrazin and colleagues (2004; 2007) as we deemed their basic experimental setup suitable for our experimental endeavor.

Within a series of experiments, Sarrazin et al. (2004, 2007) provided participants with rhythmical sequences of visual or auditory origin, i.e., either eight moving dots or eight sound beeps that simulated a moving object. Each (visual or auditory) pattern had to be reproduced from memory with spatial and temporal precision after a learning phase with either constant or variable interstimulus intervals (henceforth referred to as ISIs). Participants' reproduction accuracy and variability were considered as dependent measures. Admittedly, Sarrazin et al. (2004, 2007) pursued different experimental goals by focusing on the unfolding effects of temporal information on spatial judgments (i.e., *tau effect*) as well as effects of spatial information on temporal judgments (i.e., *kappa effect*). Nonetheless, their stimulus configurations lend themselves to examine the research question outlined above, that is, whether participants would benefit from multimodal stimulation more than from unimodal stimulation. Thus, we designed an experiment in which participants were instructed to reproduce rhythmical patterns with different ISI configurations (i.e., constant or variable ISIs) which were either presented i) auditorily (i.e., beeps), ii) visually (i.e., dots) or iii) audiovisually (i.e., simultaneous beeps and dots) to examine the impact of multimodal vs. unimodal sensory inputs within a rhythm reproduction task and to further specify the assumptions of the MAH.

If it is true that a certain task is dominated by the most appropriate (i.e., most reliable) sensory modality or that certain tasks are more appropriate to be solved within a certain modality respectively (Freides, 1974; O'Connor & Hermelin, 1972; Welch & Warren, 1980), participants' perception should be dominated by the auditory stimuli within our experimental setting. Consequently, as we chose a temporal precision task, we generally expected participants to perform better in the auditory than in the visual condition. In terms of the audiovisual condition, the MAH would predict that the most appropriate modality (i.e., here audition) attracts more attention than the less appropriate modality (i.e., here vision), resulting in a lower sensory impact of the visual modality for successful task solution (cf. Wada et al., 2003). According to Hass et al. (2012, p. 6), "in its most extreme form", the MAH predicts that only the most appropriate modality might add to participants' performance while the input from the less appropriate modality is fully neglected. If true, participants' accuracy and variability should not differ between the auditory and the audiovisual condition. Additionally, bearing in mind that an increasing temporal task complexity might lead to a more pronounced effect of modality appropriateness (cf. Welch & Warren, 1980), the difference between the auditory (or even audiovisual) and the visual condition is predicted to be larger in variable than in constant ISI configurations.

6.2 Method

Participants

Based on an estimated effect size of $\eta_p{}^2 = .20$ which is consistent with similar studies (e.g., Glenberg & Jona, 1991), a power analysis conducted in GPower (Version 3.1) resulted in a sample size of 34 participants. Considering the possibility of participant drop out, we recruited 40 participants (M_{age} = 25.7 years, SD_{age} = 3.9 years; 15 male, 25 female) who volunteered to take part in the experiment. All participants had normal or corrected-to-normal hearing as well as vision (both based on self-report) and provided informed consent prior to experimentation. The study design was approved by the ethics committee of the Faculty of Social and Behavioral Sciences of Friedrich Schiller University Jena (FSV 21/026).

Apparatus

The experiment was conducted on a desktop computer (Fujitsu Celsius M740, Fujitsu Technology Solutions GmbH, Tokyo, Japan) using a 24" screen with a refreshing rate of 60 Hz (Fujitsu P24W-7, Fujitsu Technology Solutions GmbH, Tokyo, Japan) and a wired keyboard (Fujitsu KBPC PX ECO, Fujitsu Technology Solutions GmbH, Tokyo, Japan). For the presentation of the auditory stimuli, we used over-ear headphones (Sony MDR-ZX110, Sony Corporation, Tokyo, Japan). The experiment was created using the PsychoPy3 interface (Version 2021.1.4.; see Peirce et al., 2019, see https://osf.io/ycf2s/?view_only=f0117e75e44c49adafa448c4eb872630).

Stimuli

The current experiment comprised three conditions with different stimuli setups (see Figure 6-1). Within each condition, eight stimuli were presented sequentially, thereby generating a rhythmical pattern. The design of our stimulus material (e.g., number of stimuli per pattern, variations in terms of ISI, stimulus appearance) was based on Sarrazin et al. (2004, 2007). With respect to our experimental purpose, however, we made some necessary adjustments: For the visual condition, a flashing white circle with a diameter of 9.6 cm was presented in the center of the screen. For the auditory condition, we used a sound with a frequency of 440 Hz. Within the audiovisual condition, the visual and auditory stimuli were presented simultaneously. Independent of condition, each stimulus was presented for 83 ms (i.e., stimulus duration of five frames). To implement different ISI types (cf. Sarrazin et al., 2004, 2007), the experimental stimuli were either shown with constant (i.e., equal intervals between stimuli) or variable (i.e., different intervals between stimuli) ISIs. In general, ISIs were defined as the intervals between the offset of one stimulus and the onset of the next stimulus. Similar to the experiments by Sarrazin et al. (2004, 2007), the ISIs varied between 278 ms to 795 ms (i.e., 12 to 43 frames). As far as possible, the duration of variable ISI combinations was matched to the duration of constant ISI combinations except for the shortest (278 ms) and longest (795 ms) ISIs as no other combination was capable to create the same duration. In sum, this resulted in 32 constant and 32 variable ISI configurations which were included in all three experimental conditions. A more detailed illustration of the ISI setup can be found in the Supplemental material.

Procedure

In advance of the experiment, participants were briefed about the experimental procedure. That is, they were informed about the experimental modalities (i.e., the blocked design with visual, auditory and audiovisual stimulus configurations) and the number of stimuli to reproduce for each rhythmical pattern. Participants were instructed to reproduce the given rhythmical patterns via key press (space bar) on the keyboard as temporally precisely as possible. The experimental instructions were presented on the computer screen so that the participants could control the course of the experiment on their own. The experiment comprised three experimental blocks, each of which represented one of the three experimental conditions (i.e., audiovisual vs. auditory vs. visual). Participants passed through all three blocks in counterbalanced order, yielding a classical within-subject design. There were 64 randomized trials in each block, 32 with constant and 32 with variable ISI structure. Each block started with ten practice trials in which participants received feedback about their performance (i.e., information regarding their average temporal deviation and if they were too early or too late) in order to get familiar with the stimulus material. Next, they started with the experimental trials in which no feedback was provided. In between blocks, participants were given the opportunity to take a short break. In total, the experiment included 192 experimental trials and took approximately 60 minutes to complete.

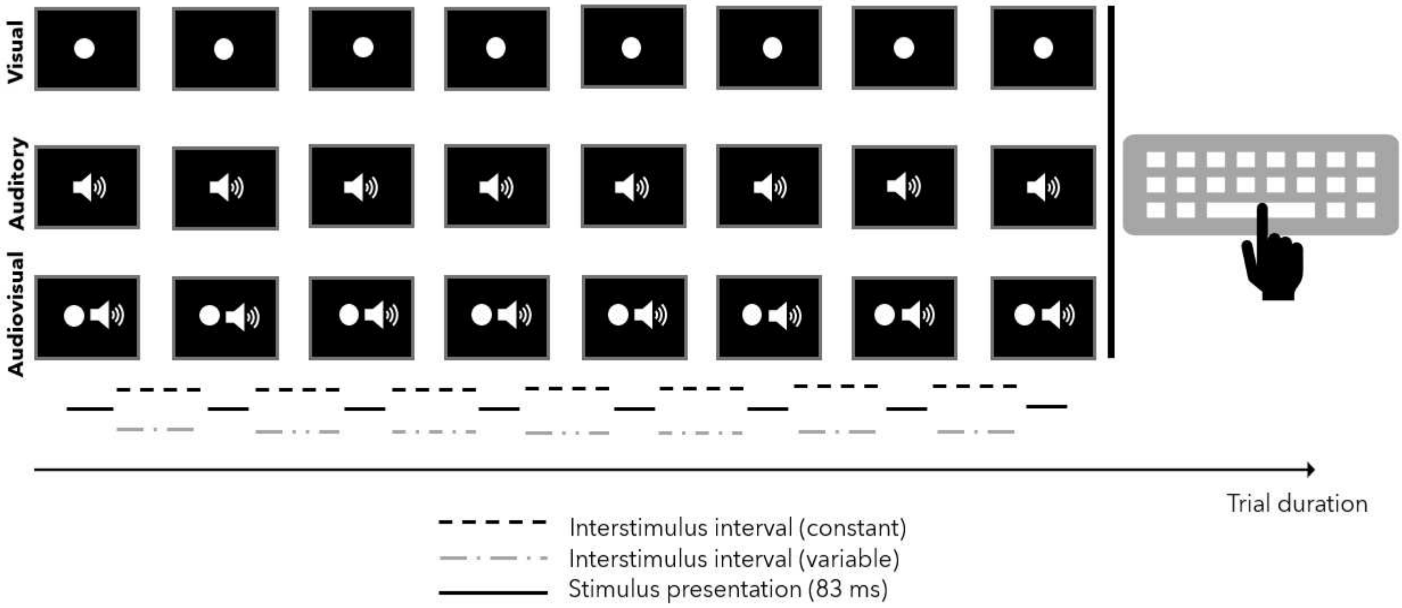

Figure 6-1. Schematic illustration of the stimulus setup and material for the three experimental conditions.

Data analysis

The temporal deviation between the presented and the reproduced ISI (i.e., the interval between two consecutive key presses) was considered our dependent measure. In particular, we calculated the constant error and the variable error in line with Welch and Warren (1980) as well as Sarrazin et al. (2004, 2007). The constant error (CE) marks the difference between participants' response time for two successive key presses (i.e., RT) and the sum of the presented ISI (i.e., provided within the rhythmical pattern; ISI_p) and the stimulus duration of 83 ms:

$$CE = RT - \left(ISI_p + 83\ ms\right)$$

It defines participants' reproduction accuracy and determines whether participants are biased to press the space bar too late or too early. The variable error (VE) describes the absolute difference between the mean constant error of a certain condition ($\bar{x}$) and the constant error (CE) of each response:

$$VE = |\bar{x} - CE|$$

It defines the deviation of the constant error from the level-specific mean (i.e., specific to subject, condition, and ISI structure). Consequently, the variable error is a measure of response-to-response variability between ISIs and strokes without the temporal bias (cf. Schutz & Roy, 1973).

Data analyses were conducted using R (Version 4.1.2, R Foundation, Vienna, Austria). To examine whether the dependent measures were affected by condition and/or ISI type according to our hypotheses, two separate 3 (condition: auditory vs. audiovisual vs. visual) by 2 (ISI type: constant vs. variable) analyses of variance (ANOVAs) were run for the constant error (reproduction accuracy) and the variable error (reproduction variability) respectively. Additionally, we conducted post-hoc pairwise comparisons with Bonferroni-Holm correction to specify the results of the ANOVAs. The effect sizes for analyses of variance are reported as partial eta squared (η_p^2). For post-hoc pairwise comparisons, we report β as an indicator for the mean difference with the corresponding 95% confidence intervals as well as Cohen's d as an effect size. Alpha was set at 0.05 for all statistical analyses.

6.3 Results[8]

CE – Reproduction accuracy

As illustrated in Figure 6-2, participants' rhythm reproduction appeared to be more accurate in the presence of auditory input. Specifically, the 3 (condition: auditory vs. audiovisual vs. visual) by 2 (ISI type: constant vs. variable) ANOVA for the constant error revealed a significant main effect for condition ($F(2,78) = 6.14$, $p = .003$, $\eta_p^2 = 0.14$). As there was neither a significant main effect for ISI type ($F(1,39) = 2.51$, $p = .122$, $\eta_p^2 = 0.06$) nor an interaction effect between condition and ISI type ($F(2,78) = 0.99$, $p = .375$, $\eta_p^2 = 0.03$), these results indicate that participants' reproduction accuracy was affected by condition only. That is, participants' constant errors differed significantly between the three conditions. Post-hoc pairwise comparisons showed significant differences with respect to participants' reproduction accuracy between the auditory and the visual ($\beta = -10.70$

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[8] Following the suggestion of an anonymous reviewer, we also calculated a Pearson's product moment correlation between the constant and the variable error to investigate the relationship between our dependent measures. The analysis revealed a negative but nonsignificant correlation ($r = -0.11$, $p = 0.48$, 95% CI [-0.41, 0.20]).

ms, 95% CI [-19.05, -2.36], *Cohen's d* = 0.41, *p* = .013) as well as the audiovisual and the visual (β = -12.23 ms, 95% CI [-20.02, -4.45], *Cohen's d* = 0.50, *p* = .003) condition. However, there was no significant difference between the auditory and the audiovisual condition (β = 1.53 ms, 95% CI [-5.35, 8.41], *Cohen's d* = 0.07, *p* = .656). In sum, participants were significantly more accurate in the auditory and the audiovisual condition. Additionally, participants generally displayed a significant bias towards an early action (see also Figure 6-2). That is, they tended to press the space bar too early independent of ISI structure (one-sampled t-test: $\bar{x}$ = -42.35 ms, 95% CI [-52.74, -31.97], *Cohen's d* = 1.30, *p* < .001).

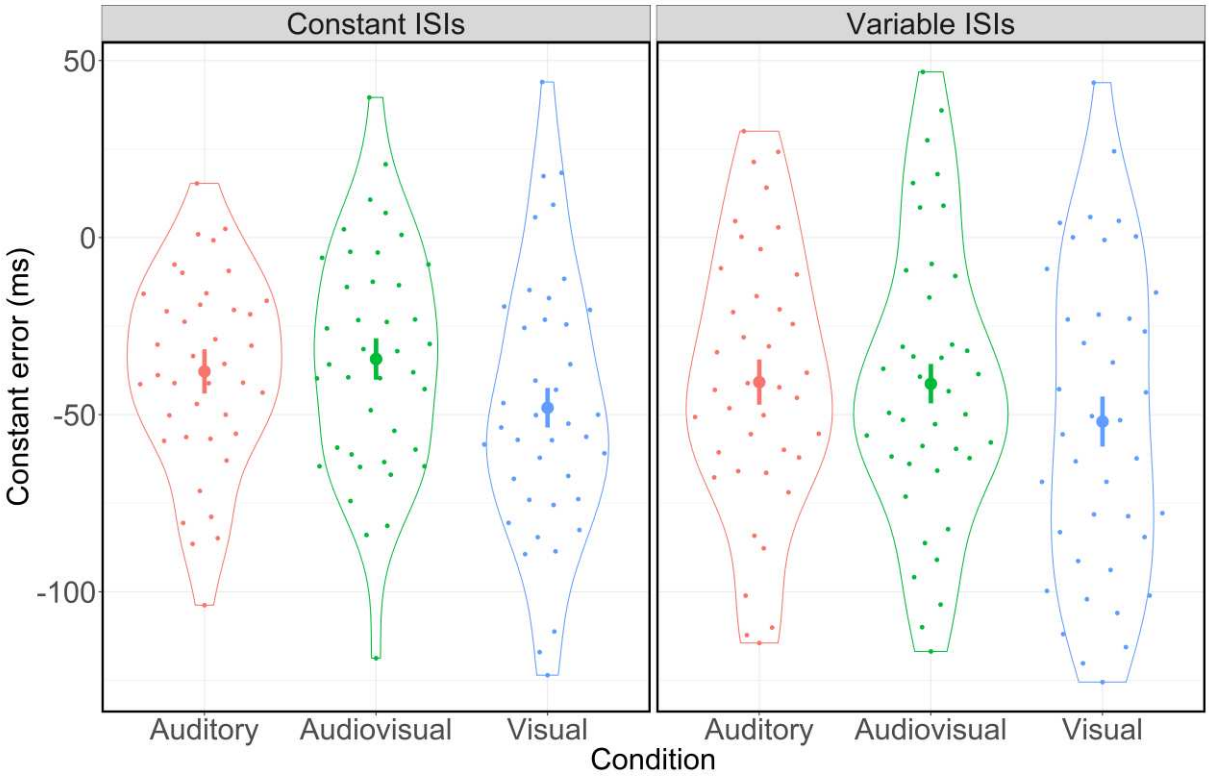

Figure 6-2. Distribution of the CE in ms for constant and variable ISIs separated by condition. Error bars indicate 95% confidence intervals. Dots represent mean values for each participant. Jitters are for clarification purposes only. *Note.* CE = constant error, ISI = interstimulus interval.

VE – Reproduction variability

As shown in Figure 6-3, participants' rhythm reproduction appeared to be less variable in the presence of auditory input. Indeed, the 3 (condition: auditory vs. audiovisual vs. visual) by 2 (ISI type: constant vs. variable) ANOVA for the variable error revealed a significant main effect for condition ($F(2,78) = 48.39$, $p < .001$, $\eta_p{}^2 = 0.55$) and for ISI type ($F(1,39) = 945.67$, $p < .001$, $\eta_p{}^2 = 0.96$), indicating that participants' variable errors differed significantly between the three conditions and between both ISI types. Additionally, there was a significant interaction between condition and ISI type ($F(2,78) = 18.84$, $p < .001$, $\eta_p{}^2 = 0.33$), revealing that the manifestation of variability differences between the three conditions was affected by ISI type.

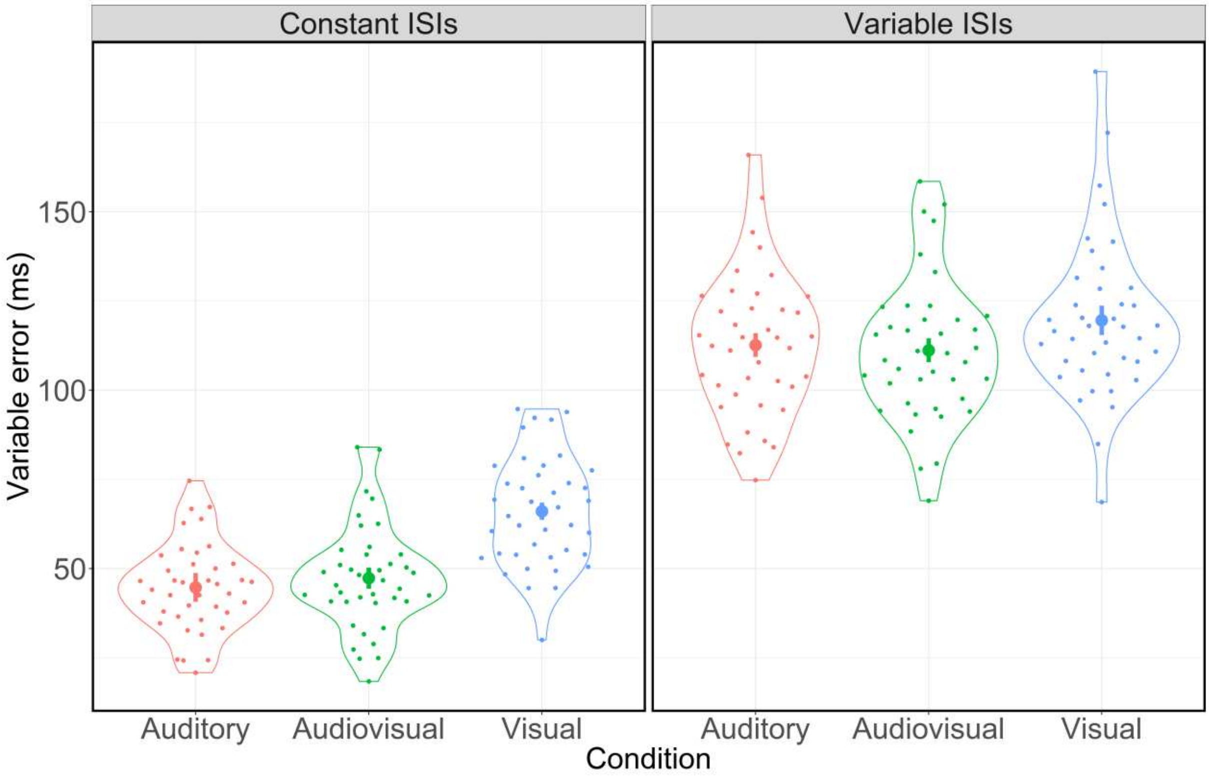

Figure 6-3. Distribution of the VE in ms for constant and variable ISIs separated by condition. Error bars indicate 95% confidence intervals. Dots represent the mean values for each participant. Jitters are for clarification purposes only. *Note.* VE = variable error, ISI = interstimulus interval.

For constant ISIs, post-hoc pairwise comparisons showed significant differences between the auditory and the visual condition ($\beta = 21.35$ ms, 95% CI [17.39, 25.32], *Cohen's* $d = 1.73$, $p < .001$) as well as between the audiovisual and the visual condition ($\beta = 18.75$ ms, 95% CI [15.19, 22.30], *Cohen's* $d = 1.69$, $p < .001$). Again, there were no significant differences between the auditory and the audiovisual condition ($\beta = 2.61$ ms, 95% CI [-0.82, 6.03], *Cohen's* $d = 0.24$, $p = .131$).

For variable ISIs, post-hoc pairwise comparisons also showed significant differences between the auditory and the visual condition (β = 6.92 ms, 95% CI [-2.10, 11.74], *Cohen's d* = 0.46, *p* = .012) as well as between the audiovisual and the visual condition (β = 8.39 ms, 95% CI [3.46, 13.32], *Cohen's d* = 0.54, *p* = 0.004). There were no differences between the auditory and the audiovisual condition (β = -1.47 ms, 95% CI [-5.14, 2.20], *Cohen's d* = 0.13, *p* = .422). That is, participants' variable error was smaller in the presence of auditory input. However, this effect was attenuated for variable ISIs.

In terms of ISI type, post-hoc pairwise comparisons revealed significant differences between the variable errors for constant and variable ISIs within the auditory condition (β = 67.92 ms, 95% CI [62.24, 73.60], *Cohen's d* = 3.82, *p* < .001), the audiovisual condition (β = 63.84 ms, 95% CI [59.19, 68.51], *Cohen's d* = 4.38, *p* < .001) and the visual condition (β = 53.49 ms, 95% CI [49.07, 57.90], *Cohen's d* = 3.87, *p* < .001). These results indicate a significant increase of participants' reproduction variability for variable ISIs in all conditions.[9]

6.4 Discussion

According to the modality appropriateness hypothesis (MAH), when solving a task for which different sensory channels provide input, the most appropriate (i.e., sensitive or reliable) modality will dominate perception (Hass et al., 2012; Lukas et al. 2014; Welch & Warren, 1980). The current study aimed at scrutinizing the premises of the MAH in a multimodal setting by comparing the effects of non-discrepant multimodal (audiovisual) vs. unimodal (auditory & visual) stimulation in a rhythm reproduction task which had previously been identified to be favorably solved within the auditory modality (cf. Chen et al., 2002; Hove et al., 2013; Patel et al., 2005; Repp & Penel, 2004). Besides controlling for modality appropriateness, we manipulated task complexity by administering different ISIs (i.e., constant and variable; cf. Sarrazin et al., 2004, 2007) to further examine whether the effect of

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[9] Again, following the suggestion of an anonymous reviewer, we conducted two additional 3 (condition: auditory vs. audiovisual vs. visual) by 2 (ISI type: constant vs. variable) by 2 (time: first 16 trials vs. last 16 trials) ANOVAs to examine whether the magnitude and direction of the observed differences were the same at the beginning versus the end of the experiment. Results revealed that there were no significant main effects for time, no significant two-way interactions (between time and condition or time and ISI type), and no significant three-way interactions (all *p* > 0.19). This was true for both the constant and the variable error.

modality appropriateness would be more pronounced in more complex tasks, that is, the variable ISI conditions as opposed to the constant ISI conditions (Welch & Warren, 1980).

Results mainly confirmed our predictions with respect to the MAH. First, participants were significantly more accurate and less variable in the auditory condition than in the visual condition across both ISI types indicating that our paradigm reliably induced effects of modality appropriateness in favor of the auditory modality. Second, and addressing the main research question whether in a multimodal stimulus environment, an additionally available but *less* appropriate modality may or may not add to solving the task, there were no significant differences between the auditory (unimodal) and the audiovisual (multimodal) condition with respect to both dependent measures and ISI types. If, as discussed by Andersen et al. (2005) as well as Welch and Warren (1980), the appropriateness of a sensory modality is closely related to directing attention towards the most reliable modality, our results might indicate that attentional resources in the audiovisual condition were (solely) focused on the auditory stimuli while the visual stimuli were disregarded (cf. Chen et al., 2002; Hass et al., 2012; Repp & Penel, 2004; Wada et al., 2003; Welch & Warren, 1980).

Additionally, our findings might be in line with Lukas et al. (2014) who claim that temporal tasks would always be dominated by auditory input – even if different sensory inputs are available. In keeping with Matuz et al. (2019), this dominance effect results from processing differences between auditory and visual stimuli in temporal tasks. That is, visual stimuli transport less accurate temporal information and also require more cognitive resources to be processed which is why participants' pattern reproductions within the audiovisual condition might have been essentially and primarily guided by auditory stimuli (cf. Repp & Penel, 2004). Interestingly, our participants subjectively confirmed this assumption reporting in an exit interview after the experiment that they had mainly focused on the auditory input in the audiovisual condition.

As introduced before, Welch and Warren (1980) hypothesized that a more complex task (i.e., in terms of spatial or temporal demands) would result in a more pronounced effect of modality appropriateness. In line with Sarrazin et al. (2004; 2007), we therefore manipulated temporal task complexity by implementing constant as well as variable ISIs. Our results do not support the original assumption. Although our results generally revealed more accurate and less variable performances for the auditory (and the audiovisual) condition across both constant and variable ISIs, the effects were smaller as concerns performance variability in variable ISI conditions than in constant ISI conditions. That is, variable errors were i) significantly larger across all conditions with variable ISIs when compared to constant ISIs and ii) the differences between the auditory and the visual as well as between the audiovisual and the visual condition diminished. One methodological explanation for this finding might be that our ISI manipulations (i.e., variable ISIs) may not only have increased *temporal* task complexity, but rather *general* task complexity. Supposing that a more pronounced effect of appropriateness would manifest by an increased difference in variance between the auditory and the visual condition, it might even be possible that our ISI manipulations caused the opposite effect as the appropriateness of the task might have actually decreased. If true, the smaller differences between conditions might indicate that the non-dominant (i.e., less appropriate) visual modality which had no additional effect on perception within constant ISIs increasingly contributed to participants' performance to overcome perceptual uncertainty within variable ISIs (Welch & Warren, 1980). Regardless, the modality appropriateness effect in favor of the auditory modality proved robust independent of ISI type.

Next to the modality appropriateness effect, results revealed a bias towards acting early, as demonstrated by a consistent shift in the constant error, indicating that participants' key presses were consistently too early. This tendency seems to be in line with the so-called negative asynchrony as introduced by Repp (2005). In his review, Repp (2005) highlighted that in tapping tasks participants' taps generally tend to precede the external rhythm (see also Yang et al., 2019). However, with respect to our results, this early bias was significantly more pronounced in the visual condition. In this regard, Jäncke et al. (2000) suggest that auditory stimuli generate an internal rhythm (i.e., a kind of internal pacemaker) whereas visual stimuli do not or less so due to their lower temporal resolution. Assuming that this internal rhythm crucially assists a temporally precise rhythm reproduction as it might lead to a more robust and durable internal representation of the rhythmical patterns (Chen & Spence, 2017; Holcombe, 2009), one might speculate that the earlier responses in the visual condition might corroborate the attempt of the visual system to compensate for the deficit in generating an internal rhythm.

In the remainder of the discussion, we would like to address further directions for future research on the interaction of sensory modalities. First, although our data indicate a dominance effect of the most appropriate modality for task solution, current approaches such as Bayesian integration models (see e.g., Colombo & Seriès, 2012; Körding et al., 2007; Körding & Wolpert, 2004; Turner et al., 2017) clearly advocate a weighting hypothesis according to which the variable error would be expected to be lowest under multimodal conditions due to the highest informational value and the statistically optimal integration of multiple sources of information respectively (Alais & Burr, 2004; Ernst & Bülthoff, 2004; Körding & Wolpert, 2004). Informational value or the explained variance of each sensory source per se can be calculated properly. Interestingly, an initial, preliminary Bayesian analysis based on our data (for details, see Supplemental material), does not confirm this assumption as the corresponding estimate for audiovisual integration differed significantly from the actual standard deviation within the audiovisual condition. Although further research and analyses are certainly needed, our exploratory analysis also supported the modality appropriateness effect in favor of the auditory modality.

Second, as already stated by Lukas et al. (2014), future research would be well-advised to further scrutinize the effects of (temporal) task complexity on modality appropriateness not only in terms of general task properties (Gil & Droit-Volet, 2011) but also with respect to other factors such as stimulus location (Kliegl & Huckauf, 2014), the presence of a second task (Brown, 2008), the attention aligned to the stimulus (Macar et al., 1994; Tse et al., 2004), affective states (Angrilli et al., 1997) or temporal coincidence between auditory and visual stimuli (Jones &

Jarick, 2006). As already suggested by Sarrazin et al. (2004; 2007), it would also be noteworthy to examine (interindividual) differences in the manifestation of modality appropriateness effects. This is particularly interesting with respect to rhythm reproduction ability and memory capabilities as some studies already introduced, for instance, age effects in temporal estimation (Espinosa-Fernández et al., 2003) as well as gender differences in memory recall (Baer et al., 2006).

To conclude, the current study provided evidence for the MAH in a rhythm reproduction task. That is, rhythm reproduction was most accurate and precise when the most appropriate modality "audition" was available. In addition, when audiovisual information was available, the additional presence of less appropriate visual information did not add to rhythm reproduction but was instead discarded.

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Supplemental material

Detailed setup of ISI configurations

Within the main article, we briefly introduced the use of 32 constant as well as 32 variable ISI configurations which were matched according to their duration. For the sake of transparency, detailed data for each ISI are provided in Table 6-S1 (for constant ISIs) and Table 6-S2 (for variable ISIs).

Table 6-S1. Constant ISI configurations. Listed below, the 32 constant ISI configurations are illustrated in more detail including the respective ISI sequence as well as the total trial duration (i.e., the sum of the seven ISIs for each trial).

ISI configuration	ISI (in ms) sequence	Total trial duration in ms
1	278	1946
	278	
	278	
	278	
	278	
	278	
	278	
2	295	2065
	295	
	295	
	295	
	295	
	295	
	295	
3	311	2177
	311	
	311	
	311	
	311	

	311	
	311	
4	328	2296
	328	
	328	
	328	
	328	
	328	
	328	
5	345	2415
	345	
	345	
	345	
	345	
	345	
	345	
6	361	2527
	361	
	361	
	361	
	361	
	361	
	361	
7	378	2646
	378	
	378	
	378	
	378	
	378	
	378	
8	395	2765

	395	
	395	
	395	
	395	
	395	
	395	
9	411	2877
	411	
	411	
	411	
	411	
	411	
	411	
10	428	2996
	428	
	428	
	428	
	428	
	428	
	428	
11	445	3115
	445	
	445	
	445	
	445	
	445	
	445	
12	461	3227
	461	
	461	
	461	

	461	
	461	
	461	
13	478	3346
	478	
	478	
	478	
	478	
	478	
	478	
14	495	3465
	495	
	495	
	495	
	495	
	495	
	495	
15	511	3577
	511	
	511	
	511	
	511	
	511	
	511	
16	528	3696
	528	
	528	
	528	
	528	
	528	
	528	

17	545	3815
	545	
	545	
	545	
	545	
	545	
	545	
18	561	3927
	561	
	561	
	561	
	561	
	561	
	561	
19	578	4046
	578	
	578	
	578	
	578	
	578	
	578	
20	595	4165
	595	
	595	
	595	
	595	
	595	
	595	
21	611	4277
	611	
	611	

	611	
	611	
	611	
	611	
22	628	4396
	628	
	628	
	628	
	628	
	628	
	628	
23	645	4515
	645	
	645	
	645	
	645	
	645	
	645	
24	661	4627
	661	
	661	
	661	
	661	
	661	
	661	
25	678	4746
	678	
	678	
	678	
	678	
	678	

	678	
26	695	4865
	695	
	695	
	695	
	695	
	695	
	695	
27	711	4977
	711	
	711	
	711	
	711	
	711	
	711	
28	728	5096
	728	
	728	
	728	
	728	
	728	
	728	
29	745	5215
	745	
	745	
	745	
	745	
	745	
	745	
30	761	5327
	761	

	761	
	761	
	761	
	761	
	761	
31	778	5446
	778	
	778	
	778	
	778	
	778	
	778	
32	795	5565
	795	
	795	
	795	
	795	
	795	
	795	

Table 6-S2. Variable ISI configurations. Listed below, the 32 variable ISI configurations are illustrated in more detail including the respective ISI sequence as well as the total trial duration (i.e., the sum of the seven ISIs for each trial).

ISI configuration	ISI (in ms) sequence	Total trial duration in ms
1	311	2062
	278	
	278	
	295	
	311	
	278	
	311	
2	295	2062
	278	
	278	
	278	
	311	
	311	
	311	
3	278	2179
	278	
	295	
	311	
	461	
	278	
	278	
4	278	2296
	361	
	428	
	278	
	295	
	361	

	295	
5	411	2413
	345	
	278	
	395	
	311	
	295	
	378	
6	311	2529
	461	
	328	
	395	
	378	
	278	
	378	
7	295	2646
	311	
	345	
	311	
	278	
	361	
	745	
8	311	2763
	345	
	278	
	361	
	545	
	528	
	295	
9	378	2880
	428	

	295	
	395	
	478	
	428	
	478	
10	545	2997
	345	
	411	
	578	
	295	
	545	
	278	
11	795	3113
	528	
	395	
	295	
	478	
	311	
	311	
12	395	3229
	278	
	328	
	611	
	661	
	628	
	328	
13	495	3346
	778	
	328	
	311	
	428	

	295 711	
14	511 478 645 411 445 295 678	3463
15	611 545 278 761 361 328 695	3579
16	461 511 478 561 278 678 728	3695
17	478 745 511 328 645 695 411	3813
18	428	3930

	678 345 395 745 578 761	
19	461 761 711 728 711 278 395	4045
20	711 711 511 445 678 511 595	4162
21	478 445 778 478 795 511 795	4280
22	795 728 361 661	4395

	611 778 461	
23	295 778 778 628 728 661 645	4513
24	778 578 728 795 645 761 345	4630
25	728 511 661 545 795 795 711	4746
26	295 778 745 761 761 728 795	4863

27	661	4979
	795	
	778	
	628	
	661	
	711	
	745	
28	645	5096
	795	
	728	
	711	
	761	
	761	
	695	
29	795	5213
	628	
	778	
	795	
	711	
	761	
	745	
30	795	5330
	728	
	761	
	795	
	745	
	778	
	728	
31	795	5447
	795	
	795	

	728	
	778	
	761	
	795	
32	778	5447
	711	
	795	
	795	
	778	
	795	
	795	

Multimodal Bayesian estimation of variance

In the discussion section of the main article, we referred to a Bayesian estimation of variance as an alternative model for the perception of multimodal inputs. To investigate whether participants exerted Bayesian inference, we compared the standard deviations from a Bayesian estimator with our empirical data. According to the Bayesian equation, the combination of information from multiple sensory sources (here auditory and visual) improves the precision of the estimate. A Bayesian posterior variance (σ^2_{Post}) of the audiovisual condition is given by the following equation (assuming normal distributions of the posterior distributions under all conditions):

$$\sigma^2_{Post(i)} = \frac{1}{\frac{1}{\sigma^2_{vis(i)}} + \frac{1}{\sigma^2_{aud(i)}}} \tag{1}$$

, where $\sigma^2_{vis(i)}$ is the variance of response time from the visual conditions and $\sigma^2_{aud(i)}$is the variance of the response time for the auditory condition for every individual (i) separately.

Figure 6-S1 displays the standard deviation ($\sqrt{\sigma}$) for the Bayesian estimation compared to the other conditions. The standard deviation for the audiovisual Bayes estimation was smaller than the empirical audiovisual standard deviation, especially in terms of variable ISIs. This difference is also illustrated by the significant interaction from the 2 (condition: audiovisual (Bayes) vs. audiovisual) by 2 (ISI type: constant vs. variable) ANOVA (see Table 6-S3) and the following post-hoc pairwise comparison between the audiovisual vs. audiovisual (Bayes) condition for each ISI type (see Table 6-S4). These results indicate that participants did not perform Bayes optimal multimodal estimations.

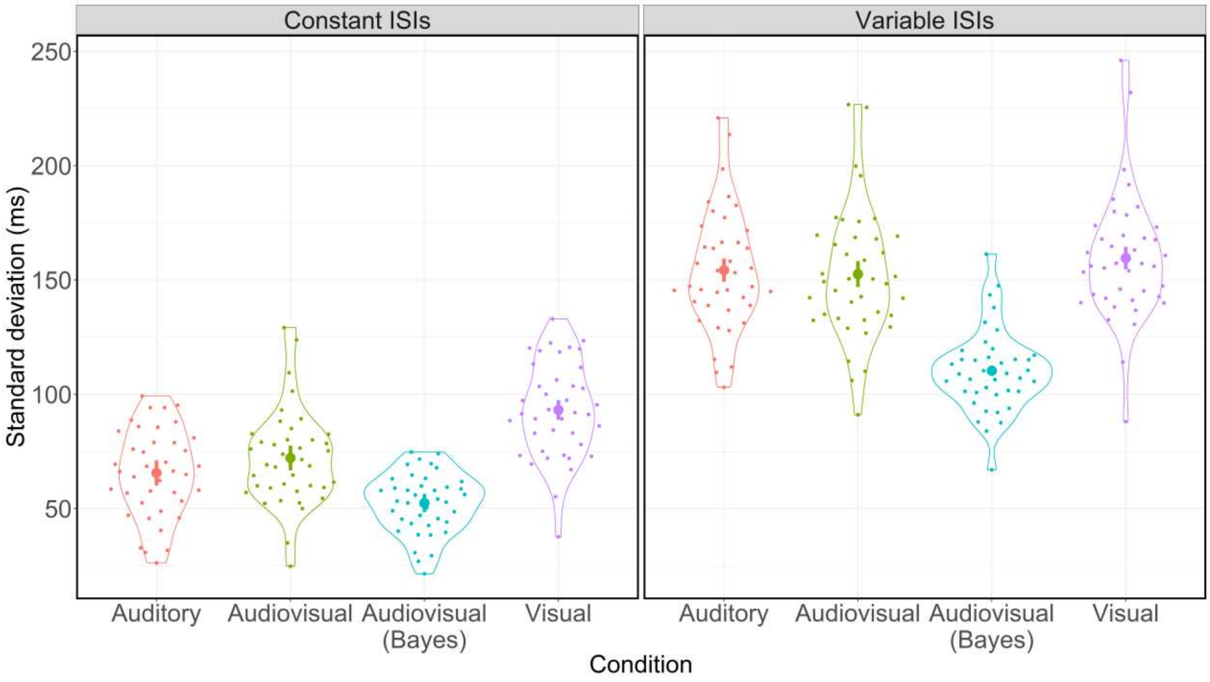

Figure 6-S1. Distribution of the standard deviation in ms for each condition separated by ISI type. As illustrated, the Bayesian estimate for audiovisual integration would predict the lowest standard deviation for the combination of both sensory sources due to the assumption of highest informational value. However, this was not the case for the actual standard deviation of the audiovisual condition in our experimental setting.

Table 6-S3. ANOVA statistics. The 2 (condition: audiovisual vs. audiovisual (Bayes)) by 2 (ISI type: constant vs. variable) ANOVA for standard deviation revealed significant main effects for condition and ISI type as well as a significant interaction between condition and ISI type.

Effect	F (1, 39)	p	η_p^2
Condition	187.12	<0.05	0.828
ISI type	640.99	<0.05	0.943
Condition x ISI type	35.493	<0.05	0.476

Table 6-S4. Post-hoc pairwise comparison for the audiovisual vs. the audiovisual (Bayes) condition. With respect to the significant 2x2 interaction, post-hoc pairwise comparisons between the empirical and the Bayesian standard deviation for the audiovisual condition were conducted for both ISI types.

ISI type	Group 1	Group 2	t (39)	Diff (ms)	95% CI (ms)	p
constant	audiovisual (Bayes)	audiovisual	-6.45	-19.71	[-25.90 to -13.5]	<0.05
variable	audiovisual (Bayes)	audiovisual	-14.87	-42.27	[-48.02 to -36.52]	<0.05

CHAPTER 7

GENERAL DISCUSSION

7 GENERAL DISCUSSION

The current publication-based thesis aspired to scrutinize the contributions of visual and auditory information to the coordination of complex rhythmic motor tasks with special emphasis on the task of long jumping. Given that the visual system has been characterized by a higher sensitivity in spatial tasks while the auditory system is assumed to be dominant within temporal tasks (see e.g., Aschersleben & Bertelson, 2003; Lukas et al., 2014; Näätänen & Winkler, 1999; O' Connor & Hermelin, 1972; Recanzone, 2003; Recanzone, 2009; Sandhu & Dyson, 2012; Shimojo & Shams, 2001; Spence & Squire, 2003; Welch & Warren, 1980; Welch et al., 1986), we hypothesized that the integration of visual and auditory information might be crucial for the successful execution of the long jump run-up as it requires a combination of both spatial (i.e., precise hitting of the take-off board) as well as temporal precision (i.e., maintaining a rhythmic stride pattern) to leap as far as possible.

First, as concerns the importance of *visual* input for the successful coordination of the rhythmic motor task of long jumping, previous research has identified a gait-based parameter (i.e., the maximum standard deviation of toe-board distance) which is assumed to indicate a reduction in step variability based on visual regulation processes (cf. Hay & Koh, 1988). Since this parameter of *gait-based visual regulation* has been commonly proposed in the context of long jumping but has never been validated by means of direct measures, the first study of this thesis (Hildebrandt & Cañal-Bruland, 2020; Chapter 4) aimed to investigate the long jump run-up by means of mobile eye-tracking technology to test whether the gait-based parameter of visual regulation can be affirmed by a respective gaze parameter. Second, although recent studies emphasized the importance of *auditory* information for the execution of complex motor tasks and corresponding motor control (see e.g., Kennel et al., 2015; MacPherson et al., 2009; Schaffert et al., 2020), the effects of auditory feedback on the rhythmic coordination of the long jump run-up have not been examined so far. Accordingly, the second empirical study of this thesis (Hildebrandt & Cañal-Bruland, 2021; Chapter 5) was designed to examine the impact of auditory feedback on the rhythmic motor coordination of the long jump run-up by implementing two different auditory manipulations (i.e., auditory deprivation, delayed auditory feedback). Third, as the second study revealed some unexpected results in terms of the auditory deprivation, that is, a facilitation effect on participants' gait and gaze patterns during the run-up instead of performance decrements (cf. Schaffert et al., 2020), a final empirical study (Hildebrandt et al., 2022; Chapter 6) was conducted to validate the reported effects within a more controllable and less constrained laboratory setting by using the task of motor rhythm reproduction as a more simplified rhythmic motor task.

While the first empirical investigation of this thesis did indeed suggest a *gaze-based* equivalent (i.e., the longest gaze on the take-off board) to gait-based visual regulation and underlined the importance of *visual* input for the successful coordination of the run-up (cf., Hay & Koh, 1988; Lee et al., 1982), the second empirical examination revealed that present *auditory* feedback seemed to be of rather subordinate importance to fulfill the special requirements of the long jump run-up and may even impair participants' gait and gaze behavior as well as jumping performance when presented in a delayed manner. In a similar vein, the final laboratory investigation of this thesis demonstrated that auditory information only might be sufficient to successfully reproduce given rhythmical patterns whereas additional visual input did not significantly contribute to task solution.

7.1 Theoretical discussion

1) The longest gaze on the take-off board coincided with the parameter of gait-based visual regulation (i.e., maximum standard deviation of toe-board distance).

Within our study, gait-based regulation was initiated on average five steps from the take-off board, thereby corroborating the findings of previous studies (see e.g., Berg et al., 1994). Intriguingly, the apparent connection between the well-established gait-based parameter of visual regulation and our gaze-based suggestion represents a novel finding and underpins the importance of visual information for the long jump by demonstrating that not only gait parameters but also gaze parameters contribute to the rhythmic coordination of the run-up and the “online control of movement” (Klostermann et al., 2013). In addition, the reported coincidence between the parameter of gait-based visual regulation (i.e., mechanism to reduce step variability to precisely hit the take-off board) and the longest gaze on the take-off board seems to support our initial theoretical deliberations (see Chapter 4.1). That is, given that fewer fixations of longer durations have been associated with more stable and better motor performances (Mann et al., 2007; Vickers, 1996, 2009), we suggested that the longest gaze on the take-off board might be equally relevant to maintain adequate movement stability for an optimal take-off. Therefore, in keeping with the de Rugy et al. (2002), the coincidence between the parameter of gait-based visual regulation and the longest gaze on the take-off board (i.e., visual input serving the reduction of motor variability) seems to support perception-action coupling as a driving control mechanism for the execution of the run-up (see also Panteli et al., 2016; Renshaw & Davids, 2004).

2) Manipulated (i.e., absent or delayed) auditory feedback affected participants’ gait and gaze patterns and, to some extent, outcome performance.

The assumptions about a continuous perception-action coupling mechanism during the long jump run-up might also directly account for the findings of the second empirical study as both auditory manipulations differently affected our behavioral gait and gaze measures during the rhythmic motor coordination of the long jump run-up as well as the resulting jumped distance to some extent.

Different from what we were expecting and in contrast to the findings by Schaffert et al. (2020), it seemed that absent rather than present auditory feedback facilitated participants’ gait and gaze behavior while there were no differences between present vs. absent auditory feedback with respect to participants’ jumped distance. More specifically, participants displayed shorter step lengths in the acceleration phase and longer steps in the zeroing-in phase in the absence of auditory feedback. In fact, these results revealed that participants’ gait behavior was closer to the prototypical (ideal) run-up pattern (see Lee et al., 1982) when no auditory feedback was present. Further, participants showed less variable gaze patterns in the absence of auditory feedback. In sum, these facilitating effects of the auditory deprivation on our gait and gaze measures appeared to be rather counterintuitive and in conflict with our original predictions as we hypothesized that *present* auditory feedback (i.e., multimodal context with visual and auditory input) would result in more stable gaze patterns and better motor performance (Klostermann et al., 2013; Klostermann & Moeinirad, 2020; Mann et al., 2007) in keeping with the commonly advocated perceptual advantage of available multisensory input (Alais & Burr, 2004; Alais et al., 2010; Ernst & Banks, 2002; Shams et al., 2005; Stein & Stanford, 2008; Stein et al., 2014; see Chapter 2.1).

As concerns the effects of the second auditory manipulation on the rhythmic motor coordination of the long jump run-up, our results revealed that the delayed auditory feedback negatively affected all three behavioral measures in agreement with our hypotheses. That is, in keeping with the findings by Kennel et al. (2015), participants showed significant deviations from the ideal run-up pattern (Lee et al., 1982) with shorter step lengths across both phases of the run-up. Similarly, participants' gait behavior was significantly less stable in the delayed feedback condition indicating that the delayed auditory feedback prevented participants' from displaying their habitual gaze routine when compared to the concurrent auditory feedback condition. Beyond, given that more stable gaze patterns are associated with better motor performance (Klostermann et al., 2013; Klostermann & Moeinirad, 2020; Mann et al., 2007), the increasing variability in participants' gaze behavior as a result of the delayed auditory feedback (Shams et a., 2004) might also explain participants' poorer jumping performance.

Additionally, in line with the elaborations by Chase et al. (1961), the delayed auditory feedback might have significantly impaired the integration of visual and auditory information thereby corroborating the importance of temporal correspondence between visual and auditory input (see Chapter 2.2.2) for the optimum coordination of the long jump run-up (see e.g., Bolognini et al., 2005, 2010) and probably pointing out the limits of the temporal window for audiovisual integration (Meredith et al., 1987). That is, temporally disconnected visual and auditory stimuli, for instance, due to a delay in the auditory modality, seem to hamper the integration process (see e.g., Kadunce et al., 2001). In this regard, bearing in mind that it might be of particular relevance for the optimal integration of visual and auditory information in the context of long jumping that both sensory inputs are assumed to have a common cause, participants' assumption of unity (Chapter 2.2.3) might have been violated by the delayed auditory feedback.

Alternatively, our results concerning the delayed auditory feedback may account for the ideomotor theory (Shin et al., 2010) which is providing a theoretical framework for action planning. The theory is promoting the fundamental idea that goal-directed actions (e.g., reaching and pressing a light switch) are represented by their anticipated results, that is, action effects (e.g., illumination of a room). As early as 1997, Finney put this notion to the test by manipulating the action effects of a learned skill, e.g., playing the keyboard. Results revealed that participants' response time to initiate their keypresses, as well as their error rates, increased when the sound produced by keypress (i.e., action effect) was delayed. In a similar vein, as the auditory feedback of step sounds during the long jump run-up might equally represent action effects to produce a rhythmical run-up pattern, the delayed auditory feedback might have been detrimental to the successful activation of the respective action effect and consecutive action planning.

Taken together, the partially quite counterintuitive results of the two experiments within the second study might indicate that both auditory manipulations underlie different mechanisms. That is, the absent auditory feedback during the run-up might have enhanced the processing of the remaining – especially visual - sensory inputs (cf. Araneda et al., 2016; Brodoehl et al., 2015) and eventually led to a more concentrated alignment of attentional resources (Chapter 2.2.4) to the visual modality as supported by the more stable gaze patterns under auditory deprivation (Chase et al., 1961). Therefore, it seems as if the absent feedback from the auditory stream could be well-compensated by other sensory modalities. In contrast, concerning participants' modified gait and gaze patterns as well as their decreased jumped distance, the delayed auditory feedback might have impaired participants' temporal perception of the sensory event (cf. Wolpert & Ghahramani, 2000, see Chapter 2.2.2) and the respective online error-correction (cf. Hossner et al., 2015). As a result, participants' perturbed motor routine as well as the less stable gaze patterns might represent a rather unsuccessful attempt of the visual system to compensate for the deviant auditory input (cf. Castiello et al., 2010; Desmurget & Grafton, 2000).

Interestingly, from the perspective of the MAH (Welch & Warren, 1980, see Chapter 2.3.3), there might be an overarching explanation for these findings. That is, as the absent auditory feedback did not lead to any deteriorations but facilitation effects while the delayed auditory feedback supposedly affected participants' gaze patterns with adverse consequences for their motor behavior and performance, one might hypothesize that the long jump – at least with respect to our investigations - might be a rather visually dominated task for which the auditory modality seems to be of subordinate relevance. In other words, as our participants did not benefit more from multisensory (i.e., audiovisual) stimulation than from unimodal stimulation (i.e., visual), the visual modality appears to be the most appropriate (i.e., reliable) modality for the optimal rhythmic motor coordination of the run-up thereby dominating perception in the multimodal setting of long jumping (Hass et al., 2012; Lukas et al. 2014; Welch & Warren, 1980) and revealing effects of intersensory bias towards vision (Chapter 2.3).

3) The auditory modality dominates perception in motor rhythm reproduction.

Concerning the quite unexpected effects of the auditory deprivation on participants' gait and gaze patterns during the long jump run-up and based on the fundamental premises of the MAH (cf. Welch & Warren, 1980), a final study was conducted within a more controllable and simplified laboratory setting to validate whether information from the most appropriate (i.e., reliable) modality only might be sufficient for successful task solution. As we hypothesized that the findings from the second investigation should replicate within an *auditorily* dominated task setting as well, the auditorily favored (cf. Chen et al., 2002; Hove et al., 2012; Patel et al., 2005; Repp & Penel, 2004) task of motor rhythm reproduction was chosen to compare the impact of multimodal (i.e., audiovisual) vs. unimodal (i.e., auditory or visual) stimulus input on reproduction accuracy and to investigate whether participants benefit more from multimodal than from unimodal stimulation.

As hypothesized and in keeping with the premises of the MAH, participants' rhythm reproduction was significantly more accurate and less variable in the presence of auditory input (i.e., in the auditory and in the audiovisual condition) for both constant as well as variable ISIs. More importantly and as concerns the comparison between multimodal vs. unimodal stimulus input, there were no significant differences between the auditory and the audiovisual condition across both ISI types indicating that the auditory (i.e., most appropriate) modality only was sufficient for precise task solution whereas the visual (i.e., less appropriate) modality did not significantly add to participants' reproduction performance. In this regard, one might speculate that participants' attentional alignment (Chapter 2.2.4) in the audiovisual condition was predominantly focused on the auditory input whereas the visual input was mostly neglected (cf. Chen et al., 2002; Hass et al., 2012; Repp & Penel, 2004; Wada et al., 2003; Welch & Warren, 1980). In keeping with Matuz et al. (2019), this dominance effect results from processing differences between auditory and visual stimuli in temporal tasks. That is, visual stimuli transport less accurate temporal information and also require more cognitive resources to be processed which is why participants' pattern reproductions within the audiovisual condition might have been essentially and primarily guided by auditory stimuli (cf. Repp & Penel, 2004). Interestingly, our participants subjectively confirmed this assumption reporting in an exit interview after the experiment that they had mainly focused on the auditory input in the audiovisual condition. In contrast to the notion by Welch and Warren (1980), however, this effect has not been identified to be more distinct within variable (i.e., more complex) rhythmical patterns. To summarize, contrary to the generally promoted advantage of multisensory stimulus input (i.e., multimodal stimulus configurations) for faster and more accurate performance (see also Luan et al., 2021), our experimental data revealed that participants do not benefit more from multimodal stimulation than from unimodal stimulation within a task for which the most appropriate modality is already known.

Taken the findings of our three studies together, the results contributed to a more sophisticated understanding of the multisensory interplay between visual and auditory information as well as outcome performance in complex rhythmic motor tasks indicating that, depending on the specific requirements of the task itself, visual and auditory information did not equally contribute to perception and succeeding action. While the findings of the second study clearly advocate the occurrence of intersensory bias (cf. Chapter 2.3) towards the visual modality within the long jump setting, they might even suggest effects of *multisensory depression* (Stein & Stanford, 2008) as the multimodal stimulation (i.e., both visual and auditory input provided) appeared to be less efficient than unimodal (i.e., visual) stimulation for the execution of the long jump run-up, at least concerning participants' gait and gaze patterns. Although these effects could not be fully replicated within the final study of this thesis, the results in terms of participants' reproduction accuracy for constant ISIs revealed an interesting tendency as the respective comparison between the auditory and the audiovisual condition marginally failed to reach significance. That is, participants' reproduction accuracy decreased in the multimodal (i.e., audiovisual) condition. Accordingly, this tendency might indicate a quite similar effect suggesting that additional input from the less appropriate modality might be detrimental to successful task solution to some extent.

Overall, the advantages of unimodal stimulation (i.e., auditory deprivation in Chapter 5, auditory condition in Chapter 6) appear to be in conflict with what we were originally expecting and the commonly proposed advantages of MSI (i.e., multimodal stimulation) for perception and proceeding action as initially introduced within Chapter 2.1 (Alais & Burr, 2004; Alais et al., 2010; Calvert & Thesen, 2004; Ernst & Banks, 2002; Rowland et al., 2007; Shams et al., 2005; Stein & Stanford, 2008; Stein et al., 2014). Interestingly, although Bayesian integration models (see e.g., Colombo & Seriès, 2012; Körding et al., 2007; Körding & Wolpert, 2004; Turner et al., 2017) usually predict explained sensory variance to be lowest under conditions of multimodal stimulation (Alais & Burr, 2004; Ernst & Bülthoff, 2004; Körding & Wolpert, 2004), a preliminary Bayesian analysis (see Supplemental material in Chapter 6) also corroborated our findings and provided additional support for the MAH within our experimental settings. Moreover, our results might underpin the commonly advocated hypothesis of weighting sensory inputs according to their informational value or reliability (see Chapter 2.3.1; Burr & Alais, 2006; Ernst & Banks, 2002; Shams et al., 2005).

Finally, from a theoretical and more fundamental perspective, our experimental series provided evidence for the occurrence of intersensory bias as a result of the model-based interaction between situational influences, modality characteristics and observer processes (Welch & Warren, 1980; see Chapter 2.3.3). In this regard, the experimental designs of the investigations in Chapters 5 and 6 targeted audiovisual integration during the complex rhythmic tasks of long jumping and motor rhythm reproduction by successfully manipulating situational influences (i.e., stimulus properties). That is, stimulus intensity (i.e., present vs. absent visual/auditory feedback) as well as temporal correspondence between visual and auditory input (i.e., concurrent vs. delayed auditory feedback; see also Chapter 2.2.2) have been modulated to scrutinize the multisensory interplay between visual and auditory inputs. Additionally, specific characteristics of the modalities, for instance, the superior temporal precision of the auditory modality, have been intentionally considered within the experimental trajectory (cf. Chapter 6). In turn, regarding our experimental results and the strong effects of intersensory bias, there is reason to assume that our experimental manipulations have also altered i) participants' subjective impression of a common spatiotemporal source of sensory inputs (cf. UA, Welch & Warren, 1980), for instance, by delaying auditory feedback (Chapter 5) and ii) their attentional alignment towards the most appropriate modality within an explicitly modality-appropriate task (Chapter 6). Among other methodological considerations, the role of participants' crossmodal experience, formalized as expertise, will be reviewed within the next section of this discussion.

7.2 Methodological considerations

While the empirical findings of the current thesis have been discussed from a theoretical perspective in the previous section, the following section will now address some methodological considerations concerning sample characteristics as well as experimental methods per se which certainly should be taken into account with respect to the generalizability of the experimental results.

7.2.1 Sample characteristics

Expertise

First of all, especially with respect to the field-based examinations in the long jump setting, participants' perceptual (cf. crossmodal experience, Chapter 2.2.1) as well as motor expertise might be a factor of particular importance concerning the overall manifestations of our outcome measures. Although we ensured that all our participants in the first two studies had adequate experience in long jumping due to their educational curriculum, their performances, competition experiences and training frequencies (i.e., key aspects of athlete expertise, see Swann et al., 2015) were by no means comparable to expert athletes which are – admittedly – a rarely exclusive and hard-to-reach sample. Therefore, as already discussed within the respective sections of the empirical studies, it cannot be ruled out that an expert sample would have revealed different results with respect to our gait-based and gaze-based measures as well as jumping performance.

Gait measures & Jumping performance

As concerns our gait-based measures and the parameter of gait-based visual regulation in particular, our results generally support the assumption by Panteli et al. (2014) that this parameter is not an exclusive attribute to expert performance but a rather "ever-present" feature that is independent of the level of athletes' expertise. However, in contrast to the findings reported by Bradshaw and Aisbett (2006) on an earlier onset of gait-based visual regulation being associated with further jumped distances, our data did not suggest any connection between these two variables – potentially due to the differences between their sample (i.e., elite athletes, $M_{Jumped\ distance}$ = 6.18 m) and our sample (i.e., rather inexperienced sport science students, $M_{Jumped\ distance}$ = 4.39 m across the three long jump experiments). Hence, although it seems that visual regulation, at least from a gait-based perspective, is present in athletes of all skill levels (i.e., novices, intermediates, or experts; see also Berg et al., 1994; Scott et al., 1997), gait-based visual regulation might contribute to experts' coordination of the long jump run-up to a different extent and with different consequences for athletes' locomotion. As concerns the findings by Bradshaw and Aisbett (2006) and given that expert athletes usually display superior jumping performances when compared to novices, one might even speculate that elite long jumpers generally show an earlier onset of gait-based visual regulation. Consequently, if true that the onset of gait-based visual regulation marks the transition between the two phases of the long jump run-up as suggested by Lee et al. (1982), an earlier onset of gait-based visual regulation might be equivalent to a shorter acceleration phase in expert athletes.

Gaze measures

In a similar vein, we cannot rule out that participants' level of expertise has also been affecting their gaze patterns. While gaze behavior is generally considered a crucial determinant of successful motor performance (Hüttermann et al., 2018; Land & McLeod, 2000; Vickers & Williams, 2007; Williams & Davids, 1998), two seminal meta-analyses by Mann et al. (2007) and Gegenfurtner et al. (2011) have reported that experts' gaze behavior is characterized by significantly fewer fixations of longer duration when compared to novices' gaze behavior. In addition, Savelsbergh et al. (2002) identified a more consistent gaze behavior (i.e., comparable gaze patterns across trials) in expert athletes. Consequently, expert athletes are commonly assumed to have attained spatial and temporal knowledge of task-relevant cues (Mann et al., 2007) resulting in superior abilities in picking up and extracting relevant information from their (visual) environment (Hüttermann et al., 2018; Williams et al., 1993).

Hence, as i) differences in athletes' gaze behavior between different levels of skill have been addressed within various studies to date (for an overview, see Gegenfurtner et al., 2011; Mann et al., 2007) and ii) our three field-based studies were the first to our knowledge to apply portable eye-tracking technology to the setting of long jumping in a somewhat exploratory manner, the general validity of our gaze-based visual regulation parameter (i.e., the longest gaze on the take-off board) and its temporal coincidence with the gait-based visual regulation parameter should be ratified within an expert sample.

Susceptibility to (manipulated) auditory feedback, crossmodal experience & modality appropriateness

When reviewing the comparatively small number of studies addressing the effects of auditory feedback or auditory manipulations respectively on sports performance (e.g., see Schaffert et al., 2019 for a recent review), it seems as if the impact of absent auditory feedback might also depend on participants' level of expertise within the respective sports domain. As already addressed above, our findings on the facilitating effects of absent auditory feedback on participants' gait and gaze behavior during the long jump run-up are not in line with the investigation by Schaffert et al. (2020). That is, in contrast to our participants, the elite rowers in the study by Schaffert et al. (2020) were significantly impaired by the absent auditory feedback (e.g., sound of the paddle plunging into water) in terms of movement precision. Similar effects were also reported in an early study by Takeuchi (1993) who showed that the match performance of experienced tennis players decreased under auditory deprivation.

Although the disciplines of long jumping, rowing, and tennis certainly require different movement patterns and have unique spatial and temporal demands, one might hypothesize that expert athletes do not only excel superior capabilities in extracting spatially and temporally relevant cues from the visual modality but also obtain substantial information for the effective rhythmic coordination of movement from the auditory modality. In other words, it might be possible that an expert sample of long jumpers would have been more susceptible to the absent auditory feedback due to their more pronounced and more distinct crossmodal experience (i.e., making use of all available multisensory cues from the environment, efficient information pick-up; cf. Hüttermann et al., 2018). Moreover, if true that absent auditory feedback does not impair inexperienced (i.e., less skilled) athletes' gait and gaze coordination as they might not be able to effectively use auditory information during the run-up, this may even imply a more pronounced modality appropriateness effect (i.e., stronger bias towards the visual modality) in less experienced athletes.

As concerns participants’ susceptibility to delayed auditory feedback, our findings on the negative effects of delayed auditory feedback on our outcome measures comply with the results by Kennel et al. (2015) in hurdle jumping, who have also examined a sample of sport science students, however, with significantly more competition experience. Accordingly, as the effects of delayed auditory feedback seem to be present in different levels of athletes’ expertise and different disciplines, this might corroborate the idea of different mechanisms underlying both our auditory manipulations as already outlined in Chapters 5.4 and 7.1. That is, delayed auditory feedback (i.e., erroneous sensory information, cf. Hossner et al., 2015) might invariably impair participants’ gait, gaze, and motor performance whereas the impact of absent auditory feedback (i.e., less sensory information available) on participants’ performance might depend on participants’ level of motor expertise and their experience in effectively using inputs from different sensory sources. However, given the relatively small number of comparable studies examining the effects of auditory feedback on different outcome variables and motor performance in sports so far, this hypothesis is highly speculative.

Finally, with respect to the experimental task of motor rhythm reproduction (see empirical investigation in Chapter 6), it might also be worthwhile to review the effects of expertise and higher crossmodal experience in this special setting. As a matter of fact, and similar to research on expert-novice differences in gaze behavior, there are a plethora of studies dedicated to identifying differences between trained musicians (i.e., experts) and non-musicians (i.e., less-skilled participants) concerning different types of rhythm reproduction tasks, for instance, sensorimotor synchronization (i.e., following an external rhythm with rhythmic movement; see Repp, 2005). In this regard, a review by Repp and Su (2013) revealed that reproduction variability is significantly lower in professional musicians when compared to non-musicians (see also Repp, 2010; Repp & Doggett, 2007) and that this effect is getting more pronounced with increasing expertise (Repp et al., 2013). Hence, although these previous studies on sensorimotor synchronization predominantly included auditory stimulation, a validation of our findings within an expert (i.e., trained musicians) sample might also be interesting with respect to motor rhythm reproduction in a multimodal setting. In fact, as musicians can be described as *auditory experts* (cf. Sandhu, 2011), their perceptual expertise in favor of the auditory modality (e.g., better temporal reproduction; Rammsayer & Altenmüller, 2006) might even bias their perception in a multimodal setting (Tanaka & Curran, 2001) leading to an even more pronounced modality appropriateness effect (i.e., stronger bias towards the auditory modality) in motor rhythm reproduction.

Sample size

Apart from participants' expertise, sample size might be another aspect that should be critically discussed – not only in terms of our first two studies but with respect to the empirical validity of field-based eye-tracking investigations in general. To start with, as concerns previous research on (gait-based) visual regulation in long jumping, it is prominent that seminal studies (see e.g., Bradshaw & Aisbett, 2006; Lee et al., 1982; Scott et al., 1997; Panteli et al., 2016; Theodorou et al., 2011; Theodorou & Skordilis, 2006) have typically relied on relatively small sample sizes, i.e., on average 7.33 participants, to gain knowledge about the relationship between visual processes and gait regulation during the long jump run-up. Additionally, most of the aforementioned studies also favored the use of post-hoc analyses of pre-recorded competition videos instead of conducting proper experimental trials resulting in comparatively low experimental control. While the small sample sizes in long jumping research may partially result from the naturally limited access to and availability of expert long jumpers and thereby represent a general issue in expertise research (cf. McAbee, 2018), however, Haas (2012) emphasized the importance of an adequate sample size to i) achieve high statistical power within an experiment, ii) ensure empirical validity and iii) draw generally valid conclusions.

In this regard, the mean sample size of 19.3 participants across our three field-based examinations did not only exceed the sample size of similar studies in long jumping but is also in line with the findings of a recent review by Kredel et al. (2017) revealing an average sample size of 20.6 participants in field-based eye-tracking studies within different sports tasks. Concerning this matter, Hagemann et al. (2006) stated that the relatively small sample sizes within eye-tracking examinations in general are closely intertwined with the complex and time-consuming analyses of gaze measurements - especially when conducting manual gaze analyses as in our case. That is, as the special characteristics of the experimental setting (i.e., participants' permanent movement including head and gaze shifts) did not allow for an automatic mapping (i.e., automatic fixation identification within the defined AOIs by BeGaze software), our gaze analyses were performed frame-by-frame for a total of 696 trials thereby supporting Hagemann et al.'s assumption (see also Chapter 7.2.2). Beyond, although we seemingly managed to recruit an acceptable number of participants for our experimental purposes, we did not only rely on p-values to evaluate our findings but additionally calculated effect sizes to cautiously interpret the novel findings of our innovative studies. However, to overcome potential problems of statistical power in prospective (field-based) studies with or without eye-tracking technology, it is certainly recommended to conduct an a-priori power analysis as in the last study of this thesis (Hildebrandt et al., 2022) to determine the required sample size and to set the scene for robust effects based on adequate data sets (cf. Faul et al., 2007; Tomczak et al., 2014).

7.2.2 Experimental methods

With respect to the research questions of the first two studies (Chapters 4 and 5), the development of an adequate experimental design to investigate visual regulation and effects of (manipulated) auditory feedback in long jumping was severely challenged by a trade-off between high ecological validity on the one hand and high experimental control on the other hand. Concerning the former, previous sports psychological research increasingly called for more ecologically valid experimental paradigms outside the laboratory to reliably investigate perceptual-cognitive aspects of athlete performance under naturalistic conditions and draw substantial conclusions for athletes and coaches (cf. Araújo & Davids, 2009). Interestingly, this claim has also been specifically highlighted in sports-related eye-tracking research (see Kredel et al., 2017) given that the vast majority (i.e., 69%) of these studies is still conducted in the laboratory setting despite the flourishing improvements in technology and mobility (Hüttermann et al., 2018).

Hence, as concerns the field-based experiments of this thesis, we aspired to strike a balance between demands of validity and experimental control. That is, we designed a representative and ecologically valid experimental paradigm (i.e., representing real-world circumstances, cf. Brunswick, 1956) in the setting of long jumping in which participants' instructions and motor responses naturally complied with actual competitional behavior (Araújo et al., 2007; Mann et al., 2007) while targeting experimental control by implementing a standardized and task-specific warm-up procedure and a predefined experimental protocol. Finally, within the more simplified and less constrained laboratory task of motor rhythm reproduction, we were able to validate the findings of our field-based examinations under conditions of high experimental control thereby allowing to transfer our results from the field to the lab.

In addition, we successfully integrated the technology of mobile (i.e., head-mounted) eye-tracking into our two field-based studies thereby being the first studies to our knowledge to ever examine the long jump run-up by means of actual gaze tracking. Although the methodological approach of eye-tracking has been widely proposed to access an athlete's cognitive processing (i.e., information about the attentional alignment and temporal processing of stimuli) via gaze behavior (Carter & Luke, 2020; Discombe & Cotterill, 2015; Hüttermann et al., 2018; Moran, 2009), some flaws of the technology concerning basic characteristics of the eye-tracking system per se, properties of the experimental procedure and participants' behavior needed to be managed for a successful empirical implementation within our field-based setting (cf. Ehinger et al., 2019; Hutton, 2019):

First of all, the eye-tracking equipment used within the first three experiments (i.e., the SMI ETG-2.6-1648-844 by SensoMotoric Instruments, Teltow, Germany) was a common video-based system using infrared light to illuminate the eye to measure the position of the respective corneal reflection relative to the pupil[10]. Due to their manner of functioning, eye-tracking systems like the SMI ETG are therefore not only very sensitive to lighting in general, their tracking quality is also massively dependent on an adequate illumination of the pupil (Discombe & Cotterill, 2015). That is, participants' gaze-tracking can be impaired by partially occluded pupils (e.g., due to fatigue) or erroneous pupil identification (e.g., due to painted lashes or eye lids). Similarly, the corneal reflection can be masked by other reflections (e.g., glasses, hard contact lenses, or sweat drops) which might also inhibit good tracking quality. Concerning our experimental setup, we tried our best to take these potential difficulties into account. To start with, we followed the mandatory recommendation (see e.g., Carter & Luke, 2020; Kredel et al., 2017) to perform a (three-point) system calibration multiple times during the experimental procedure to check for an accurate identification of the corneal reflection and position of the pupil thereby ensuring high gaze-tracking quality. Moreover, participants were instructed to neither wear make-up such as mascara or eye shadow nor glasses or hard contact lenses on the day of the experiment. Additionally, participants' sweat was wiped off regularly.

Further, the head-mounted mobile setup of the SMI eye-tracking system, i.e., special glasses which were connected to a smartphone recording unit, enabled our participants to move as freely as possible during the long jump run-up (Discombe & Cotterill, 2015). However, as inferred by Carter and Luke (2020), this increased mobility might in turn cause a decrease in gaze-tracking quality for two main reasons. First, mobile eye-trackers usually operate with a lower sampling frequency than stationary eye-trackers leading to a poorer spatial and temporal resolution of participants' gaze behavior. For instance, the stationary system *EyeLink 1000* can record participants' gaze behavior with a sampling frequency up to 1000 Hz (see Ehinger et al., 2019). Second, as eye-tracking investigations within representative experimental paradigms are accompanied by higher degrees of

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[10] Video-based systems usually operate with two cameras. While one camera is tracking the corneal reflections and the pupil, a second camera is recording participants' field of view (Hammoud, 2008; Holmqvist et al., 2011). Both camera sources are then combined to superimpose participant's point of gaze to the real-world perspective (Kredel et al., 2017; Majaranta & Bulling, 2014).

freedom, the risk for potential motion artifacts increases, especially when the equipment is not sufficiently fixed to participants' bodies (Kredel et al., 2017). To overcome these obstacles, we recorded participants' gaze behavior with a sampling frequency of 60 Hz which was in fact twice as high as the average sampling frequency in sports-related eye-tracking research (i.e., 30 Hz, see Kredel et al., 2017). In addition, we also made sure our equipment was properly fixed to participants' heads and bodies in advance of every trial to avoid motion artifacts.

Last but not least, although eye-tracking systems with higher sampling frequencies might offer superior gaze-tracking quality, they produce an enormous amount of raw data resulting in time-consuming and complex, often even manual frame-by-frame data analyses (see Hagemann et al., 2006). However, as already illustrated in the previous section (see Chapter 7.2.1), our gaze data were analyzed manually due to participants' constant movement during the run-up and the intransparent algorithms of the automatic mapping feature in the BeGaze software. Given the large amount of generated data and the availability of various gaze parameters, one might be tempted to derive as many variables as possible from the data set, making Type 1 errors more likely to occur (Carter & Luke, 2020; von der Malsburg & Angele, 2017). To reduce the risk of Type 1 errors within our data analyses, the gaze parameters observed within the two field-based studies (i.e., dwell times on AOIs, switches between AOIs) were purposefully chosen in line with the research trajectory and the concurrent research question.

In sum, there is no doubt that eye-tracking technology can provide interesting insights into an athlete's visual behavior and cognitive processing (i.e., attentional alignment) - as long as its shortcomings are tackled efficiently. In this regard, it should also be noted that present eye-tracking technology operates on the basis of foveal vision only while peripheral vision cannot be captured by the system (Hüttermann et al., 2018). In this regard, previous research admittedly supported the notion that the direction of gaze (i.e., foveal vision) is closely intertwined with the focus of attention (see e.g., Bojko, 2013; Nakashima & Kumada, 2017; Vickers, 2009). However, gaze direction might not always be equivalent to attentional alignment (Laurent et al., 2006). In fact, some computer-based studies (e.g., Ryu et al., 2013, 2015) have shown that expert athletes also extract crucial information from the periphery to prepare for succeeding action (for recent reviews, see also Vater et al., 2020, 2022). Hence, although measuring peripheral vision under more naturalistic circumstances (see Mann et al., 2010 for an interesting approach in cricket) is representing a difficult endeavor, the role of peripheral vision for successful motor behavior should not be underestimated – maybe even in terms of long jumping performance.

Additionally, the simultaneous recording of both participants' gaze patterns (i.e., via the mobile eye-tracking system) and their gait behavior (i.e., via the camera setup) during the long jump run-up for the purpose of a subsequent, joint analysis should also be carefully evaluated. Although post-hoc video analyses seem to be common practice in long jumping research to compute participants' step characteristics such as step length (see e.g., Bradshaw & Aisbett, 2006; Lee et al., 1982), the synthesis of these sensitive methodological approaches and the respective data analyses should be controlled properly. As concerns our experimental procedure, a high-frequent and plainly audible sound was used in each trial to temporally synchronize both recording sources and to facilitate post-hoc data merging. Furthermore, the spatial dimensions of the run-up track have been attentively calibrated prior to each experimentation to meet the requirements of a post-hoc analysis of participants' step parameters.

Apart from these methodological challenges that inevitably go hand in hand with the implementation of a complex and sensitive technology such as mobile eye-tracking into a field-based experimental paradigm (for recent overviews see Discombe & Cotterill, 2015; Moran et al., 2018), applying two auditory manipulations to the long jumping paradigm turned out to be an equally difficult objective concerning the technical effort on the one hand and the synchronization of the equipment on the other hand. That is, while the integration of an auditory deprivation could be realized relatively easily through the application of ear plugs (see Schaffert et al., 2020; Takeuchi, 1993), delaying participants' auditory feedback in real-time during the run-up has been a bit more of a challenge. Fortunately, we were given the opportunity to use the original equipment from the investigation by Kennel et al. (2015) thereby ensuring a methodologically sound and field-approved approach to delay auditory feedback during the execution of a motor task. Nevertheless, concerning both methodological approaches to implement the auditory deprivation as well as the auditory delay, some aspects need to be factored in when aiming to apply these manipulations in different field-based settings. That is, while the ear plugs may have suppressed the surrounding noises and "objective" auditory feedback on participants' step sounds, we could not control whether they might have relied on "subjective" tactile and proprioceptive information instead to coordinate their run-up (see Chapter 5.2.3). As concerns the equipment by Kennel et al. (2015), the authors already stated that participants' step sounds were recorded from a lower back position instead of in-ear. Hence, this recording position and the belt per se might have constrained the naturalistic circumstances of the experimental setting and participants' normal motor routine, especially in combination with the eye-tracking equipment (i.e., glasses and recording unit). To obtain an overview of participants' subjective impressions, both aspects were integrated into the post-experimental exit questionnaire.

To disentangle the impact of both visual and auditory feedback on the coordination of the long jump run-up more in-depth, it would have been very interesting to conduct a follow-up experiment on our second empirical study including a *visual* deprivation condition as previous research, for instance by Theodorou et al. (2011, 2013), identified similar run-up behaviors in visually impaired long jumpers. However, there is reason to doubt that a field-based experimental paradigm including a visual deprivation or occlusion condition for participants with normal or corrected-to-normal vision would have been approved by the ethics committee. Hence, to validate our findings within a more controllable experimental setting, we intentionally aimed to conduct a lab-based experiment for our final empirical investigation.

In this regard, the selection of an adequate lab-based motor task has been a methodological challenge, too as we specifically aimed for a more simplified rhythmic motor task for which the most appropriate modality has been known in advance. However, as we hypothesized that the findings from the second study should replicate within an auditorily dominated task setting as well, we opted for the temporal task of reproducing different rhythmical patterns. Given that the auditory system has been characterized by a higher temporal resolution (cf. Loeffler et al., 2018; O'Connor & Hermelin, 1972; Recanzone, 2009; Sandhu & Dyson, 2012), this task has been proven to be favorably solved within the auditory modality (cf. Chen et al., 2002; Hove et al., 2013; Gault & Goodfellow, 1938; Glenberg & Jona, 1991; Kolers & Brewster, 1985; Patel et al., 2005; Repp & Penel, 2004). Additionally, as the resulting laboratory setup allowed for less restrictive inclusion criteria, participants' recruitment has no longer been limited to sports science students only.

7.3 Future directions

The current thesis contributed to our understanding of visual and auditory determinants of rhythmic motor performance by examining a complex rhythmic task in a field-based setting (i.e., long jumping) and validating the respective findings in the laboratory setting (i.e., motor rhythm reproduction). In this final chapter of this thesis, some routes for future research will be outlined before venturing an outlook on potential implications for practitioners.

First and foremost, as already discussed previously (see Chapter 7.2), statistically and methodologically sound replication studies with participants of different expertise levels (i.e., novice, intermediate and expert long jumpers) should be considered to evaluate the presented findings on both visual as well as auditory influences on different behavioral measures such as gait patterns, gaze behavior and jumping performance. In this regard, the persistence of the coincidence between the gait-based and the gaze-based visual regulation parameter which has been identified within the first empirical study (Chapter 4) should be put to the test. Beyond, the effects of and the susceptibility to (manipulated) auditory feedback depending on the level of expertise should be considered in further detail as our experiments (Chapter 5) could only partially corroborate previous research (cf. Schaffert et al., 2020). Additionally, an extension of our experimental paradigm to similar sports disciplines (e.g., see Kennel et al., 2015 for hurdle jumping; Makaruk et al., 2015 for triple jumping) might be conceivable as well. Moreover, lab-based re-evaluations of the respective findings (Chapter 6) are highly recommended to transfer insights from field-based experiments to more fundamental paradigms and vice versa.

Further, our pioneering field-based studies in the setting of long jumping have once more exemplified the promising potential of eye-tracking technology to access athletes' visual behavior as well as the underlying cognitive processes, especially when employed in a mobile (i.e., head-mounted) manner. Given that the SMI ETG system including the supplied BeGaze software analyzed the obtained gaze data based on inaccessible and intransparent algorithms (see Chapter 7.3.2), however, the use of other eye-tracking systems with more transparent and flexible open-source software solutions might be desirable for future research. For instance, the various configurations of the *Pupil lab* system (for a systematic overview, see Kassner et al., 2014) offer an upscaled head-mounted eye-tracking system with high spatial and temporal resolution including an open-source analyzing software to customize gaze analyses according to the respective experimental endeavor (see also Ehinger et al., 2019). Further, Kredel et al. (2017) recently suggested combining mobile eye-tracking investigations with other promising technologies such as motion capture systems to directly record participants' movements simultaneously with their gaze behavior in order to control for potential movement artifacts (e.g., head movements, see Chapter 7.2.2) and to systematically correlate gaze events and motor responses. Thereby, post-hoc video analyses to calculate step characteristics (see Chapters 4 and 5) might be avoidable. Apart from the motion capture approach, virtual reality settings have also been linked to eye-tracking technology (e.g., Hayhoe & Ballard, 2005) as they comprise innovative opportunities to conduct ecologically valid experiments under quasi naturalistic circumstances on the one hand, but also allow for high experimental control in terms of eventual visual or auditory manipulations on the other hand (Heilmann & Witte, 2021). Intriguingly, a recent study by Miller et al. (2017) applied both motion capture and virtual reality environments in combination with eye-tracking technology to examine visuomotor integration tasks. In sum, as concerns field-based as well as fundamental research, future studies would be well-advised to benefit from these promising technological approaches to gain further knowledge about multisensory integration processes in complex motor tasks.

Interestingly, the findings of our empirical studies might not only inspire future research on the interplay between the senses but might also comprise some significant insights for practitioners like athletes and coaches. As early as 1995, Coffey and Reichow stated that comparisons between expert and novice athletes, for instance, in terms of gaze behavior during motor performance, may serve the identification of the most efficient and successful gaze strategies thereby allowing to draw direct conclusions for the improvement of novices' performance (see also Baker et al., 2003). Following this logic and bearing in mind the association between (gait-based) visual regulation and jumped distance (Bradshaw & Aisbett, 2006), replicating our eye-tracking experiments with expert athletes would not only enable us to investigate whether expert jumpers reveal the same visual strategies (i.e., coincidence between gait-based and gaze-based visual regulation) but also to derive potential training implications for novices.

Additionally, if true that the efficient use of auditory feedback during the long jump run-up is depending on the level of participants' expertise, i.e., that it might be learned due to a more pronounced crossmodal experience, an expert-novice comparison with respect to the effects of (manipulated) auditory feedback might also offer an interesting perspective to explicitly incorporate different types of auditory information into the training process. In fact, previous studies seem to corroborate this idea as the visually impaired long jumpers in the investigations by Theodorou et al. (2011, 2013) successfully executed the long jump run-up while obtaining additional auditory instructions on the location of the take-off board from their coaches. In a similar vein, Kennel et al. (2015) suggested integrating expert-generated, naturalistic movement sounds into novices' training to significantly improve their motor performance. In this regard, the seminal investigation by Agostini et al. (2004) already provided supporting evidence for the effectiveness of additional auditory feedback in hammer throwing as the motor performances of their participants significantly improved after stimulation with the naturalistic sounds (i.e., hammer-air contact) associated to their best personal throws.

Apart from implementing naturalistic movement sounds into the training process, there is growing evidence that athletes’ motor learning and execution can also benefit from rather artificial auditory feedback, that is, movement sonification (see Chapter 5.1; Effenberg et al., 2016). This technique involves the sonification of different kinematic parameters including modulations in pitch and volume to increase athletes’ awareness of certain aspects of movement and relevant cues to practice and master stable motor performance. Over the last decades, sonification has already been proven successful within a variety of different sports (for recent reviews see Schaffert et al., 2019; van Rheden et al., 2020). As a matter of fact, previous studies have shown that sonification can even improve different aspects of running performance (e.g., Godbout et al., 2014) which in turn appears to be an essential part of the run-up in long jumping. Hence, the technique of sonification might assist long jumpers like Olympic gold medalist Malaika Mihambo to identify and practice their optimal run-up rhythm.

To conclude, the initial quote by Stein et al. (2014; see Chapter 2) highlighted that perception and proceeding action are rarely limited to information from one sensory modality only as various sensory cues are available within the environment. However, as illustrated by the empirical results of the current thesis, the efficient use of *all* available sensory cues seems to be closely intertwined with the specific requirements (e.g., spatial or temporal demands) of a certain task - especially concerning the coordination of rhythmic motor tasks. For this reason, future research should embrace the multimodal requirements of complex rhythmic motor tasks to exploit the promising potential of multisensory interventional approaches for sports performance.

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AUTHOR CONTRIBUTIONS

STUDY 1

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STUDY 2

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Authorship contribution statement:

Alexandra Hildebrandt – Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Project administration.
Rouwen Cañal-Bruland – Conceptualization, Resources, Writing – review & editing, Supervision.

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Eric Grießbach – Formal Analysis, Writing – review & editing.
Rouwen Cañal-Bruland – Conceptualization, Resources, Writing – review & editing, Supervision.

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Jocelyn Bell Burnell sagte einmal:

„Die Wissenschaft geht nicht immer vorwärts. Es ist ein bisschen wie ein Zauberwürfel. Manchmal musst du mit einem Zauberwürfel mehr Chaos anrichten, bevor du es richtig machen kannst."

Dieses Zitat erscheint mir sehr treffend, wenn ich nun auf die letzten viereinhalb Jahre meines (Wissenschaftler-)Lebens zurückblicke. Ich durfte sowohl Momente großen Glücks erleben, mich über spannende Befunde und akzeptierte Artikel freuen und Teil eines großartigen Arbeitsbereichs werden. Gleichzeitig musste ich jedoch auch die ein oder andere Hürde nehmen, mich den Konsequenzen einer weltweiten Pandemie stellen und den Umgang mit (wissenschaftlichen) Rückschlägen erlernen. Doch auch zu Zeiten, in denen der „Zauberwürfel" Promotion an einigen Stellen hakte, gab es Menschen und Institutionen, die immer bedingungslos hinter mir standen und mir geholfen haben, den Würfel an den richtigen Stellen zu drehen.

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

Datum	Unterschrift