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ELITE BIATHLON

An Interdisciplinary Approach to Unravel the
Intricate Links Between Biological, Psychological and
Social Factors Determining Biathlon Performance

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Study 1:

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1 Theoretical Background

> *“Race across the snow on skis as fast as you can. Now stop and shoot a target the size of an Oreo about 54 yards away. If you miss, you’ll ski penalty laps before you are allowed to race to the next set of targets.” (Parker-Pope, 2018).*

The above quote succinctly illustrates the Olympic Sport of biathlon; a sport which combines the challenging, yet remarkably different tasks of cross country skiing in free technique and rifle shooting. To be successful, biathletes not only have to ski fast but also have to shoot precisely and quickly under a tremendous physiological workload. In addition, a wide variety of competition formats including differing distances, numbers of shooting blocks, start regulations such as mass start or individual start and penalties demand a wide range of abilities. Consequently, there can be little doubt that this unique combination of tasks within one sport poses high demands on biological (i.e., physiological and biomechanical), psychological and also – as competitions include different social context (e.g., simultaneous shooting with co-competitors vs. individual conditions) – social determinants of performance. The complexity of elite biathlon is vividly described by the world-class biathlete Clare Egan:

> *"The physical things are difficult — using all your muscles and pumping your heart as fast as you can. [...] But the mental piece is the biggest challenge of biathlon. [...] I have this task I’ve done thousands of times that I’m trying to repeat. I know that I’m going to have distractions. The person next to me hit all of the targets. The fans are screaming. The person on the loudspeaker says, ‘Here’s Clare Egan from the U.S.A. Let’s see if she can hold it together.’" (Clare Egan in Parker-Pope, 2018).*

Having said this, research in biathlon from an applied perspective aims to give evidence-based recommendations to coaches, athletes or sport psychologists in biathlon. Furthermore, from a fundamental research perspective it offers an ideal testbed to gain insights into processes underpinning the interaction of high physiological workload and fine motor control and to extend our knowledge of biological, psychological and social performance determinants in an environment of high expertise.

However, as outlined in a recent review by Laaksonen and colleagues (2018), biathlon-specific research is scarce when being compared to research in cross country skiing and mainly focuses on physiological and biomechanical aspects of biathlon performance while further viewing angles such as psychological determinants have only been partly investigated. In fact, most of the research examines these determinants in isolation rather than in conjunction, an approach that does not seem to be justified with regard to the complexity of biathlon.

Consequently, the present thesis aims at contributing to the current understanding of biathlon performance by applying an interdisciplinary and holistic approach to explain, predict and consequently optimize biathlon performance. In this thesis, I will first introduce biathlon by giving some background information before discussing the state of the art in biathlon-specific research. In the following, a biopsychosocial framework of biathlon performance is established, calling for interdisciplinary approaches and the integration of social context in future research. Based on this framework, the aim of the current thesis that is building interdisciplinary bridges in biathlon research and focusing on social aspects is presented before resulting research questions and work program are outlined. Methodological considerations and a description of the development and validation of an eye tracking system to measure gaze behavior in biathlon indicate the end of the introduction and lead into the main section of the thesis, comprising three empirical studies to contribute to our knowledge about performance determining factors in biathlon.

1.1 Biathlon – A Brief Description

In this chapter, some background information on biathlon is provided, in particular for those readers who are less familiar with this sport. To do so, first the historical evolution will be briefly sketched out. Next, the rules of competition including different competition formats, skiing, shooting and overall biathlon performance are explained.

History

The word *biathlon* derives from Greek and describes the combination of two contests (International Olympic Committee, n.d.). The sport of biathlon as we know it today is characterized by the combination of cross country skiing and shooting. While historical sources prove that skiing was developed about 5000 years ago, illustrations showing archers on skis suggest that human beings started to combine skiing and hunting about 1000 years later (Kirchner, 1998). Having the roots in ensuring survival by adapting to a snow-covered environment, skiing with rifles was later used by the military, especially in Scandinavia (Kirchner, 1998). The combination of skiing and shooting stepped out of the military field when a skiing competition including a shooting block of ten shots took place in Norway in the year 1912. Subsequently, the combination of cross country skiing and shooting referred to as *biathlon* and the first World Championship was arranged in 1958. Two years later in 1960, biathlon became an Olympic Sport when holding the first competitions in Winter Olympic Games in Squaw Valley (USA). Nevertheless, it took 32 more years until biathlon became an Olympic Sport for women (Kirchner, 1998).

Nowadays, biathlon has become a popular winter sport with great media attention and often more than 100.000 spectators attending a World Cup event. Several nations especially from Scandinavia, from Central and Eastern Europe, North Asia but also from North America are involved in biathlon, mirrored in athletes from ten different nations winning Olympic medals in Pyeongchang in 2018 (International Biathlon Union, 2021a). Other nations such as, for instance, China, invest in their development in this discipline with regards to future Olympic Winter Games. Since biathlon competition rules have been constantly changing since biathlon became an Olympic Sport including the introduction of new competition formats, the current state of biathlon competition rules (International Biathlon Union, 2021b) is briefly presented in the following section.

Competition Rules

According to the International Biathlon Union (International Biathlon Union, 2021b), competitors in biathlon ski a cross country course which is divided into various laps (dependent on the type of competition; typically three or five laps) and perform shooting blocks in between these laps (typically two or four shooting blocks). Depending on the type of competition and gender, the to-be-skied distance differs from three kilometers in super sprint qualification up to 15 kilometers in individual for women and 20 kilometers in individual for men. All competitions include both one or two shooting blocks in prone position and one or two shooting blocks in standing position. One shooting block comprises five targets that are presented at a distance of 50 meters, are aligned horizontally and – now I get back to the Oreo mentioned in the quote at the beginning of the introduction – have a diameter of 4.5 centimeters in prone shooting and 11.5 centimeters in standing shooting, respectively. A missed target results in a penalty that is again dependent on the type of competition and consists either in skiing an extra penalty lap of typically 150 meters or by adding an extra penalty time of one minute (International Biathlon Union, 2021b). Competition formats include individual, mass start, pursuit, sprint and relay as well as some sub-categories. Table 1 offers an overview of these regulations for senior elite biathlon, adapted from the official event and competition rules by the International Biathlon Union (2021b).

Table 1. Official regulations dependent on competition format and athlete's gender adapted from International Biathlon Union, 2021b.

	Competition Format	Competition Distance [m]	Standard Start Types, Start Intervals [sec]	Number of Skiing Loops	Shooting Sequences (P: prone, S: standing Position)	Penalty for missed Shot
MEN	Individual	20.000	Single, 30 sec	5	P-S-P-S	60 sec
	Short Individual	15.000	Single, 30 sec	5	P-S-P-S	45 sec
	Mass Start 30	15.000	Simultaneous	5	P-P-S-S	150 m
	Mass Start 60	15.000	Simultaneous	6	P-P-S-S	150 m
	Pursuit	12.500	Pursuit	5	P-P-S-S	150 m
	Sprint	10.000	Single, 30 sec	3	P-S	150 m
	Relay	7.500	Simultaneous & Tag	3	P-S	150 m
	Mixed Relay 2.5 km loop	7.500	Simultaneous & Tag	3	P-S	150 m
	Mixed Relay 2.0 km loop	6.000	Simultaneous & Tag	3	P-S	150 m
	Single Mixed Relay men first	6.000	Simultaneous & Tag	4	P-S+P-S	75 m
	Single Mixed relay men second	7.500	Simultaneous & Tag	5	P-S+P-S	75 m
	Super Sprint Qualification	4.500	Single, 15 sec	3	P-S	75 m
	Super Sprint Final	7.500	Simultaneous	5	P-P-S-S	75 m
WOMEN	Individual	15.000	Single, 30 sec	5	P-S-P-S	60 sec
	Short Individual	12.500	Single, 30 sec	5	P-S-P-S	45 sec
	Mass Start 30	12.500	Simultaneous	5	P-P-S-S	150 m
	Mass Start 60	12.000	Simultaneous	6	P-P-S-S	150 m
	Pursuit	10.000	Pursuit	5	P-P-S-S	150 m
	Sprint	7.500	Single, 30 sec	3	P-S	150 m
	Relay	6.000	Simultaneous & Tag	3	P-S	150 m
	Mixed Relay 2.5 km loop	7.500	Simultaneous & Tag	3	P-S	150 m
	Mixed Relay 2.0 km loop	6.000	Simultaneous & Tag	3	P-S	150 m
	Single Mixed Relay women first	6.000	Simultaneous & Tag	4	P-S+P-S	75 m
	Single Mixed relay women second	7.500	Simultaneous & Tag	5	P-S+P-S	75 m
	Super Sprint Qualification	4.500	Single, 15 sec	3	P-S	75 m
	Super Sprint Final	7.500	Simultaneous	5	P-P-S-S	75 m

Skiing

According to the official rules (International Biathlon Union, 2021b), biathletes start the skiing course either individually, featuring a 30 seconds or 15 seconds start interval (e.g., in individual or sprint competitions) or all athletes start simultaneously at the same time (e.g., in mass start or relay). However, there is no defined start interval for pursuit competitions but the winner of qualifying competition (typically a sprint or individual) is allowed to start first while the biathletes ranked behind are starting with a delay corresponding to the time they finished behind the winner in the qualification race. It follows that in contrast to sprint and individual races, the order of athletes in mass start, relay and pursuit is equal to the actual ranking in competition and the athletes compete next to their direct opponents on both the skiing course and the shooting range. Generally, all skiing techniques are permitted to absolve the skiing course. However, propulsion has to be generated by skis, poles and own muscular force only. The rifle as well as the required number of magazines and spare rounds have to be carried on the athlete's back (International Biathlon Union, 2021b).

Shooting

When entering the shooting range, biathletes competing in individual, sprint and super-sprint qualification are allowed to freely choose one out of typically 30 shooting lanes, provided that the targets are ready for the correct shooting position (i.e., prone or standing). However, in group start competitions such as pursuit, competitors are instructed to fill the shooting lanes sequentially starting at lane one on the very right side and taking the lowest number available. In mass start, the number of the shooting lane at the first shooting block is designated by the athletes' start number while the range is sequentially filled from lane one in the following shooting bouts (International Biathlon Union, 2021b).

The distance between the firing-line and the five circular, horizontally aligned targets is 50 meters (+/- 1 meter deviation). A target's diameter in prone shooting measures 4.5 centimeters and in standing shooting 11.5 centimeters, respectively. As illustrated in Table 1, a missed shot results in either an extra penalty lap that has to be absolved immediately after the shooting bout or a penalty time that is added to the overall competition time. The rules allow the use of a .22 caliber small-bore rifle that must weigh at least 3.5 kilograms for both men and women (International Biathlon Union, 2021b).

Overall Biathlon Performance

Based on the outlined regulations for biathlon competitions, overall biathlon performance (i.e., total race time) is composed of skiing time, shooting accuracy and shooting time. It seems reasonable that these components have different effects on overall performance that might also be dependent on competition type and its accompanying specifications such as the type of penalty: For instance, the contribution of skiing time for the final result in sprint competitions is displayed by correlation coefficients range between .58 and .82 (Cholewa et al., 2005). Notably, skiing time is a reasonable factor to distinguish between top ranked athletes (i.e., top ten) and biathletes ranked 21-30 in World Cup sprint competitions as it explains 59 to 65% of overall performance difference on both sexes (3-5% slower overall times of the lower ranked athletes; Luchsinger et al., 2018). By contrast, shooting accuracy has less but still substantial influence on the final result (correlation coefficients between .27 and .47 in sprint races; Cholewa et al., 2005) and accounts for 31 to 35% of overall performance differences (i.e., total race time; Luchsinger et al., 2018). Finally, shooting time has the slightest impact on final results with correlation coefficients between .16 and .47 (Cholewa et al., 2005) and explains 4-6% of performance differences (Luchsinger et al., 2018).

However, the impact of shooting accuracy increases in individuals compared to sprint competitions and additionally seems to differ between gender: In specific, female top ten athletes show 6% faster total race time compared to athletes ranked 21-30, while penalty time (i.e., shooting accuracy) explains 44% of these overall performance differences (Luchsinger et al., 2019). The importance of shooting accuracy in individuals is even higher for men as it accounts for 53% of differences in total race time that is 4% lower for top ten biathletes when compared to biathletes ranked 21-30 (Luchsinger et al., 2019). Skiing time explains 42 % (men) and 54 % (women) of overall performance differences. Again, range and shooting time has the smallest effect on differences in overall performance (2-3 %; Luchsinger et al., 2019).

To sum up, all of the three components contribute to the final competition result with skiing time and shooting accuracy contributing most to overall performance, thereby additionally being dependent upon competition format and gender.

1.2 Research in Biathlon: State of the Art

In this chapter, the state of the art in biathlon-specific research is introduced and discussed thoroughly. In this regard, research on biological determinants of biathlon performance (comprising physiological and biomechanical factors), studies focusing on psychological aspects and research on social factors are discussed and methodological considerations are provided. Subsequently, in Chapter 1.3, the current state of research will be summarized, unsolved questions will be identified and future routes for research will be suggested by proposing a biopsychosocial framework of biathlon performance.

1.2.1 Biological Determinants of Biathlon Performance

Physiological Factors

Cross-country skiing represents a movement that involves the whole body. With the aim of skiing as fast as possible athletes reach average skiing speeds of 6.33m/s (women) and 7.2m/s (men) in World Cup sprint competitions (Luchsinger et al., 2018). Consequently, biathlon skiing is characterized by high physiological demands that are reflected by athletes' heart rate (HR) of approximately 90% of the individual maximum heart rate (HR max) during skiing (Hoffman & Street, 1992) for a total time duration of appr. 15 minutes in sprint competitions up to appr. 45 minutes in individuals (Laaksonen et al., 2018). As the skiing course is typically divided into three or five laps, biathletes are approaching the shooting range in between these laps and HR is decreasing to an average of appr. 85-87% of HR max in a time period of appr. 50 to 60 seconds (Hoffman & Street, 1992). The following shooting bout accompanies with HR reductions to appr. 61-73% of HR max. In this regard, the physiological parameter differs substantially between shooting positions: while it drops in average appr. 28 beats per minute (bpm) during shooting in standing position, an average decrease of 47 bpm is measured in prone shooting (Hoffman & Street, 1992). Note though that the mentioned values are based on a study that was conducted almost three decades ago and biathlon has developed substantially since that time (e.g., including new competition types, faster skiing and shooting times etc.). However, to the best of my knowledge no recent peer-reviewed scientific publication has explicitly focused on physiological responses in biathlon competitions, even if one could assume that athletes and coaches are collecting these data extensively. One current master thesis was found that corroborate heart rate values around 90% of nine elite biathletes' HR max (i.e., an average of 177 bpm) in both sprint and individual competitions (Langegger, 2019).

Now, one could argue that the sport of cross country skiing in free technique and skiing in biathlon have a lot in common and biathlon-specific research on physiological factors is not necessary. Indeed, Laaksonen and colleagues (2018) noticed almost ten times as many hits in a common literature database when searching for *cross-country skiing* compared to when using *biathlon* as a key word which resulted in 79 hits. Research from cross country skiing has shown that those athletes with the highest peak oxygen uptake in relation to body-mass show fastest skiing times (Sandbakk et al., 2016) which is also true for upper body oxygen uptake (Mahood et al., 2001). In addition, it proved the effectiveness of specific training interventions on skiing performance such as heavy strength training (Losnegard et al., 2011), specific block periodization (Rønnestad et al., 2016) or aerobic high-intensity interval training (Sandbakk et al., 2013) and focused on the relation between speed and different sub-techniques, revealing increasing cycle rates and decreasing phase duration with increasing speed (Nilsson et al., 2004). An overview of success factors in cross country skiing is provided by Sandbakk and Holmberg (2014).

There can be little doubt that these results can partly be transferred to biathlon. Nevertheless, skiing in biathlon differs from cross country skiing competitions in two main aspects: On the one hand, skiing in biathlon is interrupted by shooting blocks and hence covers shorter but repetitive time durations of physiological load. Additionally, it includes the reduction of physiological workload during shooting before starting the following lap (Hoffman & Street, 1992). This interval character may have an effect on, for instance, pacing strategy and consequently on physiological demands. On the other hand, biathletes have to carry a rifle on their back weighting at least 3.5 kilograms for both female and male athletes which could affect both physiological demands but also biomechanics of skiing.

Thus far, only a few studies have specifically focused on the former aspect and examined physiological determinants in biathlon. In accordance with studies focusing on cross country skiing, Rundell and Bacharach (1995) highlighted the importance of peak oxygen uptake as this parameter was correlated with competition skiing time for male biathletes, but not for females. When focusing exclusively on female athletes, Rundell (1995) observed a relation between both maximal oxygen uptake and lactate threshold with roller skiing performance, thereby supporting the crucial role of high maximal oxygen uptakes also for women. Regarding the latter specificity of biathlon skiing, namely rifle carriage, Frederick (1987) found evidence for a possible impact of rifle carriage on biomechanics in skiing technique as horizontal velocity of the rifle turned out to be the greatest source of increased energy cost. A subsequent study by Rundell and Szmedra (1998) concluded an increased oxygen cost as well as greater ventilation and higher lactate values when roller skiing while carrying a rifle compared to conditions without a rifle. It additionally revealed a greater impact on female biathletes as well as large inter-individual ranges in energy cost that suggest the option to improve individual economies. These findings were recently corroborated and amended by the observation of an increased heart rate as well as changes in biomechanics (e.g., higher cycle rate and leg forces) when skiing with a rifle (Stoeggl et al., 2015). In contrast to previous work, Stoeggl and colleagues did not find gender-specific differences. The higher physiological demands caused by carrying the rifle are also mirrored in decreased performance in maximal roller skiing compared to roller skiing without a rifle (Jonsson Kårström et al., 2019).

Biomechanical Factors

In addition to the physiological demands athletes are facing on the skiing course, there can be little doubt that motor performance and biomechanical aspects are especially relevant when performing fast and accurate shooting. As outlined in Chapter 1.1., shooting accuracy contributes to almost the same amount to overall biathlon performance as skiing time, dependent on both competition type and gender (Luchsinger et al., 2018; Luchsinger et al., 2019). The impressive ability of expert biathletes to hit the targets of 4.5 cm (prone shooting) and 11.5 cm diameter (standing shooting) from a 50 meters distance with a heart beating appr. 85-87% of the maximal heart rate (Hoffman & Street, 1992) is mirrored in average hit rates of 92-

93% for top ten biathletes of both gender in sprint competitions (Luchsinger et al., 2018). Interestingly, men thereby shoot on average 10-11% faster than women (males: 29.4±3.9 sec in prone, 26.6±4.3 sec in standing shooting vs. females: 32.2±4.0 sec in prone, 30.3±4.6 sec in standing shooting; Luchsinger et al., 2018).

Despite the outlined crucial role of shooting for overall performance in biathlon, a large within-variability in shooting (i.e., 11-15 % for shooting time; standard deviation of proportion of hits appr. 10%, compared to within-variability of 1.5.- 1.8 % in skiing times; Skattebo & Losnegard, 2018) raises the question which factors predict shooting performance. Based on archival competition data analyses, Maier and colleagues (2018) identified the specific athlete, discipline (i.e., competition format such as mass start or sprint), shooting position (prone vs. standing shooting) and the number of shot as predictors for shooting performance. However, when using machine learning models to predict future shooting accuracy including an athlete's preceding position-specific shooting accuracy, a high degree of randomness remained (Maier et al., 2018). Given the high within-variability and randomness in shooting performance (Skattebo & Losnegard, 2018; Maier et al., 2018), studies that contribute to our understanding of the processes underpinning shooting performance are necessary. However, Laaksonen and colleagues (2018) noticed in their recent review a lack of biathlon-specific, comprehensive and systematic biomechanical studies including both shooting positions. Next to the rather descriptive competition analyses outlined above, one can differentiate between two branches of research focusing on motor performance in biathlon: On the one hand, studies analyzed motor performance in shooting without inducing previous physiological workload (i.e., looking at biathlon shooting in isolation). On the other hand, previous work was moving beyond an isolated approach and focused on physiological and biomechanical factors in conjunction by examining the impact of physiological workload on shooting performance.

In this section, I will focus on studies that looked specifically at predictors for biathlon shooting in isolation before presenting studies examining physiological and motor performance/ biomechanical factors in conjunction in the next section:

Baca and Kornfeind (2012) examined stability of aiming and rifle motion patterns by applying artificial neural networks. In specific, the authors used a camera system to measure stability and possible motion of the muzzle of the barrel in two dimensions that built the base for artificial network analysis. The study revealed that within nine elite athletes participating in this study, biathletes with higher expertise level (operationalized by their membership of the Austrian National Team) showed a more stable aiming pattern compared to biathletes classified one performance level lower (i.e., A-Team; Baca & Kornfeind, 2012). In addition, elite athletes seem to be highly adapted to the conditions of biathlon as no differences in stability between shooting on only one target compared to shooting on five horizontally aligned targets occur. Consequently, the authors assumed that the movement from one aiming line to the next is already finished before repeating (Baca & Kornfeind, 2012). Hence, there can be little doubt that elite athletes acquire a highly economic behavior to absolve the shooting block of five targets as fast and accurate as possible. Subsequently, Sattlecker and colleagues (2014) extended the examination of rifle stability under lab conditions without previous physiological workload by postural balance and its relation to shooting performance. By doing so, eight World Cup athletes, 13 biathletes attending European Cup and 15 federal youth athletes shot ten shooting bouts of five shots each. Kinematic as well as kinetic data were measured using a camera based motion capture system that allows three-dimensional analyses. In line with Baca and Kornfeind (2012), stability of the rifle (i.e., less rifle sway) seems to be a reliable predictor of shooting performance differences between biathletes attending World Cup and European Cup on the one hand and youth biathletes on the other hand. More specifically, elite athletes showed 21-23% lower total mean velocities in rifle sway compared to youth athletes (Sattlecker et al., 2014). Furthermore, findings indicated postural control as another factor distinguishing between expertise levels. In addition, the study revealed 45-64% larger deviations of the center of pressure in both legs in cross-shooting direction for youth athletes compared to elite athletes; in shooting direction, 33-77% larger deviations compared to elite athletes were measured (Sattlecker et al., 2014). Finally, a correlation coefficient between body/rifle sway and shooting performance of up to $r = .6$ was found, displaying a moderate relationship (Sattlecker et al., 2014). In conclusion, both postural control as well as rifle stability seem to play a crucial role for shooting performance under rest conditions and represent reliable factors to distinguish different expertise levels. Note though, that Baca and Kornfeind (2012) as well as Sattlecker and colleagues (2014) exclusively focused on shooting in standing position.

Physiological Factors and Motor Performance as Biological Determinants in Conjunction

As biathlon is combining tremendous physiological demands of cross country skiing with fine motor control of rifle shooting, the most pressing question beside focusing on performance determining factors of the specific tasks is *if* and *how* these two tasks affect each other. Hence, the impact of high physiological workload on motor control (e.g., the outlined performance determining factors aiming pattern, rifle stability and postural control) and consequently on shooting performance is of particular interest.

As early as in the 1980s, researchers already moved beyond an isolated approach and started to examine physiological factors and motor performance in biathlon in conjunction. The first study scrutinizing the impact of physiological exercise on body sway in standing biathlon shooting (Niinimaa & McAvoy, 1983) revealed an increase of body sway under physiological workload conditions that simulated a cross country ski race. Even if the finding of impaired postural control under physiological workload conditions was corroborated in subsequent studies (Groslambert et al., 1999; Sadowska et al., 2019) and less body sway is generally correlated with better shooting performance (Sattlecker et al., 2014), the actual effect of the outlined decreases in postural control on shooting performance has not been examined in this work. The finding of changes in biomechanics through physiological workload and its relation to shooting performance was supported by Sattlecker and colleagues (2017) when investigating factors discriminating high and low score performance in biathlon shooting: While prone shooting performance in rest condition was mainly predicted by shoulder force, the main predictor changed to vertical rifle sway when simulating a biathlon competition. In addition, both body and rifle sway were main predictors for standing shooting in rest conditions while body sway across the shooting line turned out to be the main discriminator under workload conditions (Sattlecker et al., 2017). Moreover, the importance of biomechanical factors and its changes through physiological workload seems to be dependent of aiming strategy. Köykkä and colleagues (2020) distinguished between so-called *hold* strategy that is characterized by low radial velocity with the aim of holding the aiming point as stable as possible before triggering and *timing* strategy that is characterized by higher rifle velocity as triggering is started when approaching the target. While high postural stability was related to shooting performance in both strategies under rest conditions, this was only true for biathletes applying *timing* shooting strategy under workload conditions. In addition, successful biathlon shooting using *hold* strategy was generally related to smaller distance of the aiming point mean location as well as longer time spent in this central area of the target while lower aiming point total velocity and less aiming point movement led to successful shooting in *timing* (Köykkä et al., 2020).

Subsequent studies to Niinimaa & McAvoy (1983) explicitly focused on the intricate link between exercise, rifle sway and shooting performance (Hoffman et al., 1992). In specific, 13 members of the US Biathlon Team absolved cycle ergometer exercises with heart rates of 130 bpm, 150 bpm, 170 bpm and maximal exercise before performing a shooting bout in either prone or standing position in addition to shooting bouts under rest conditions. While the measurements of shooting performance were not affected by workload level in prone position, the distance of the shots from the center of the target as well as shooting precision (operationalized as the smallest circle that encompasses the five shots) increased with increasing workload in standing shooting. In addition, the number of hits in the three highest exercise conditions decreased compared to rest conditions, but again solely in standing shooting (Hoffman et al., 1992). The finding that increased physiological workload can lead to deteriorated shooting accuracy was corroborated by Grebot and colleagues (2003) when examining shooting accuracy in ten elite biathletes immediately after skiing at 85% of individual maximum heart rate exclusively in standing position. Notably, Grebot and colleagues (2003) not only focused on the effects of physiological load on shooting performance but aimed at examining the cognitive origins of the observed performance impairment. However, cognitive function measured as the athlete’s perceptual estimation of shooting performance was not affected by skiing exercise and consequently did not explain performance decrements (Grebot et al., 2003).

Subsequently, further evidence for negative effects of exercise on shooting performance was provided by Vickers and Williams (2007): Despite being predominantly interested in psychophysiological aspects of shooting performance, they showed decreased shooting accuracy in ten members of the Canadian junior and senior national team after absolving exercises on a cycle ergometer at 55%, 70% and 85% of maximum power output as well as one maximum load. In contrast to previous studies, Ihalainen and colleagues (2018) were the first to focus on the impact of physiological load on both shooting accuracy and shooting time. To this end, eight biathletes of the Finnish national team and nine members of the junior team performed shooting bouts under rest conditions as well as immediately after roller skiing at 95% of their individual maximum heart rate exclusively in standing position. In accordance with past work (Hoffman et al., 1992; Grebot et al., 2003; Vickers & Williams, 2007), findings revealed deteriorated shooting accuracy under physiological workload compared to rest conditions in both groups. More interestingly, also shooting times seem to suffer from physiological workload as biathletes showed longer shooting times under load conditions compared to rest conditions (Ihalainen et al., 2018).

However, recent studies raised doubts on the negative effects of physiological workload on shooting performance in expert biathletes. Even if Luchsinger and colleagues (2016) primarily aimed at examining neurophysiological processes underpinning successful biathlon shooting by assessing electroencephalographic activity (EEG), they did so under rest as well as under physiological workload conditions. Workload was characterized by an intensity of 85-90% of individual maximum heart rate and was induced through roller skiing intervals. After approaching the shooting range to shoot in standing position, heart rate dropped to 60-64% of maximum heart rate. As Luchsinger et al. (2016) were also interested in expertise differences, they included nine experienced biathletes and eight cross country skiers without any experience in biathlon shooting. Findings revealed no differences in shooting performance between rest and load conditions. Interestingly, this was true for both groups even if the novices performed worse compared to the experienced biathletes in both conditions. The finding that physiological workload does not affect shooting accuracy in biathlon was corroborated by Gallicchio et al. (2016) who, similar to Luchsinger et al. (2016), predominantly focused on EEG patterns and their role for biathlon shooting. 13 experienced biathletes absolved standing shooting bouts both under rest as well as immediately after three-minutes sessions on a cycle ergometer.

In accordance with Luchsinger et al. (2016), findings did not show any changes in performance when shooting under physiological load compared to rest conditions. This finding was further corroborated by a second study of Gallicchio and colleagues (2019) that examined 13 experienced youth biathletes. Similar to Gallicchio et al. (2016) and Luchsinger et al. (2016), the authors were predominantly interested in additional predictors of successful biathlon shooting. More specifically, they focused on the role of cardiac cycle's phase for shooting accuracy both in rest and under workload conditions. Interestingly, shots with high accuracy were fired in different phases of the cardiac cycle compared to shots with low accuracy which was – in contrast to shooting accuracy – additionally dependent on the workload condition (Gallicchio et al., 2019).

Biological Determinants of Biathlon Performance: Methodological Considerations

Past research concerning the biological factors to understand, explain and predict biathlon performance have broadly focused upon two key areas: 1) the physiological factors determining skiing performance, and 2) motor performance (i.e., biomechanical factors) and its relation to shooting execution. Finally, some studies examined these factors in conjunction and specifically looked at the impact of physiological workload on shooting performance and biomechanics in shooting.

With regard to the latter branch of research, studies not only showed equivocal findings (decreased shooting performance with increasing workload level: Hoffman et al., 1992; Grebot et al., 2003; Vickers & Williams, 2007; Ihalainen et al., 2018; vs. no effects: Luchsinger et al., 2016; Gallicchio et al., 2016) but also differed remarkably in their methodological approaches and implementations. In fact, differences in the applied methods and in, for instance, ecological validity may also explain the varying findings.

First, participants' expertise level differed remarkably across the studies. For instance, even if Vickers and Williams (2007) included members of Canada's junior and senior national biathlon team, participants showed – depending on the condition – mean shooting accuracy between 42.0% (SD = 30.5%) and 74.0% (SD = 21.2%). In contrast, Gallicchio and colleagues (2016) measured percentage hit rates of 80% (SD = 14%) and 81% (SD = 10%) and hence featured a substantially higher expertise level that is close to the skill level of international top biathletes (e.g., hit rates of top ten World Cup biathletes: 92-93%; Luchsinger et al., 2018).

Second, studies applied different methodological approaches in regards to inducing physiological workload by using on the one hand cycle ergometers (Hoffman et al., 1992; Vickers & Williams, 2007; Gallicchio et al., 2016) and on the other hand roller skiing or cross country skiing (Grebot et al., 2003; Luchsinger et al., 2016; Ihalainen et al., 2018). As a consequence, physiological demands placed on the athletes varied from exclusively lower body exercise to the original skiing task involving the whole body. In addition, there was no consistent approach with regard to exercise intensity and duration. While some authors decided to increase physiological workload step-wise (e.g., rest, 55%, 70%, 85% and 100% of maximum individual VO2 capacity in Vickers & Williams, 2007), the majority of the studies focused on one specific level such as 85% of maximum individual heart rate (Grebot et al., 2003), 90% (Gallicchio et al., 2016) or even 95% of HR max (Ihalainen et al., 2018). In addition, number and duration of exercise bouts ranged between three-minutes intervals that were absolved twelve times (e.g., Gallicchio et al., 2016) up to five six-minutes intervals (e.g., Luchsinger et al., 2016). Finally, as the time period between exercising and shooting was not always defined, the actual physiological exertion when approaching the firing line remains partly unclear and might differ substantially across studies (e.g., shooting with appr. 60-64% of HR max, Luchsinger et al., 2016 vs. 87-90% immediately before shooting and 79-83% of HR max after shooting; Ihalainen et al., 2018). Consequently, the type of exercise, intensity, duration and number of exercise bouts as well as time duration between exercise and shooting affect the degree and characteristics (i.e., muscular fatigue lower body vs. upper body) of physiological fatigue and thus might have a strong impact on the results.

The third aspect concerns biathlon shooting that represents the dependent variable of the presented studies. In general, one can distinguish between biathlon shooting that follows the official rules (e.g., 50 meter shooting distance; shooting with ammunition that causes a recoil; five horizontally aligned targets with 4.5 cm and 11.5 cm diameter, respectively; e.g., Gallicchio et al., 2016; Hoffman et al., 1992) and a simulated shooting task (e.g., applying a laser system; scaled but not necessarily five targets; adapted shooting distance; e.g., Luchsinger et al., 2016; Vickers & Williams, 2007; Ihalainen et al., 2018). Additionally, with the exception of Hoffman et al.

(1992), previous work examined the impact of physiological load exclusively on standing shooting, neglecting prone position. Finally, Ihalainen and colleagues (2018) were the only ones who focused on both shooting accuracy and shooting time that comprise shooting performance, while shooting time was overlooked by all other studies.

To sum up, the large heterogeneity in applied methodological approaches results in substantial differences of studies' ecological validity. Consequently, and despite the relatively high number of studies focusing on the impact of physiological workload on shooting performance in biathlon, it seems too early to draw final conclusions about the impact of physiological workload on shooting performance in biathlon.

1.2.2 Psychological Determinants of Biathlon Performance

So far, I introduced and discussed previous research on biological factors determining biathlon performance (i.e. physiology and motor performance both in isolation and in conjunction). In this chapter, I will present biathlon-specific literature on psychological aspects to understand, explain and optimize biathlon performance.

In this regard, previous research primarily focused upon psychological interventions to enhance shooting performance or on psychological skills such as mindfulness and its relation to shooting performance. Furthermore, studies examined psychological processes such as focused attention and finally looked at the phenomenon of performing under pressure in biathlon shooting.

The first branch of research concerns intervention studies where are aimed at examining the effects of psychological interventions such as autogenic and imagery training (Groslambert et al., 2003) and relaxation (Laaksonen et al., 2011) combined with specific shooting training on shooting performance. For instance, Groslambert and colleagues (2003) conducted a six weeks standard shooting training program including sessions of one hour, four times per week with 16 expert biathletes. Subsequently, the experimental group of eight athletes received six weeks training sessions of 30 minutes four times per week covering autogenic training to decrease muscle tension as well as imagery training visualizing successful biathlon shooting and decreases in body sway. In contrast, the control group continued with standard shooting training. Standing shooting performance and rifle stability were measured at baseline conditions, after six weeks with both groups receiving the same program and at the end of the interventions. Notably, the authors aimed at high ecological validity and examined performance parameters under physiological workload conditions induced by roller skiing at 90% of individual maximal heart rate (Groslambert et al., 2003). Both groups showed improved shooting performance as well as increased rifle stability across the measurement times. Furthermore, biathletes participating in autogenic and imagery training enhanced their rifle hold significantly more compared to the control group. However, this effect failed significance for shooting performance (Groslambert et al., 2003). The potential of psychological interventions in biathlon was further investigated by Laaksonen and colleagues (2011) when examining the effects of combined relaxation and specific shooting training in 20 biathletes. Study design differed in that the control group did not receive any intervention while the experimental group participated in an *Applied Tension Release (ATR)* training for ten weeks and additionally in specific shooting training. Similar to the previous study, shooting performance was assessed during a simulated biathlon competition including sub-maximal physiological workload. Findings corroborated the usefulness of relaxation interventions in combination with specific shooting training as the experimental group enhanced shooting accuracy significantly after the intervention phase (Laaksonen et al., 2011). Note though, that both studies focused exclusively on shooting in standing position.

Excluding these intervention studies, research focusing on psychological skills and their relation to biathlon performance is scarce. One prospective study aimed at examining a temporal relationship between different sport-specific mindfulness skills and shooting performance in an actual biathlon competition (Josefsson et al., 2020). To do so, 25 biathletes completed a self-report about mindfulness and participated at four competitions within two weeks. Findings revealed dispositional mindfulness (i.e., awareness, refocusing, non-judgemental attitude) as a predictor for shooting performance, even if it only explained small proportions of variance (Josefsson et al., 2020). Another study focused on the athletes' ability to anticipate forthcoming events by prospectively controlling their cardiac response during biathlon competitions (Benum et al., 2021) and concluded that biathletes regulate their heart rate upwards before the start as well as before uphill sections and downwards before entering the shooting range. Consequently, even the youth biathletes that participated in this study seem to be able to anticipate and react physiologically to critical events in biathlon competitions (Benum et al., 2021).

While the studies described above focus on biathlon performance from a long-term perspective, another branch of research is focusing on psychological processes underpinning accurate and fast shooting.

In this regard, Gallicchio and colleagues (2016) assumed an important role of frontal-midline theta and alpha power for successful biathlon shooting and assessed electroencephalographic activity (EEG) as they are linked to monitoring processes and cortical inhibition. In addition, the authors were interested in the impact of submaximal cardiovascular load on this specific electroencephalographic activity. To this end, thirteen experienced biathletes performed in total 24 shooting blocks of five consecutive shots in standing position both under rest and immediately after 3 minutes exercise bouts on a cycling ergometer (at 90% of individual maximum heart rate). Despite the finding that physiological workload did not affect shooting accuracy, the assessment of EEG activity allowed new insights into attentional processes in biathlon shooting: Biathletes who showed higher frontal-midline theta power immediately before firing also showed better shooting accuracy – a positive effect that was also confirmed for time-series analyses within athletes. This was also true for physiological load conditions, even if the effect was smaller compared to rest conditions. Based on the result that frontal-midline theta power was generally reduced under cardiovascular load, the authors argue that fewer monitoring resources are available. At the same time, alpha power increased with physiological load, indicating an increase in cortical inhibition processes (Gallicchio et al., 2016). The crucial role of focused attention for successful biathlon shooting was corroborated by Luchsinger et al. (2016), concluding higher frontal theta activity of experts (biathletes) compared to novice shooters (cross country skiers). Similar to Gallicchio et al. (2016), this study included both shooting blocks in rest as well as under high physiological workload. In contrast to the previous study, frontal theta activity was not affected by physiological workload but remained stable for both groups, thereby displaying the ability to maintain focused attention also under high physiological workload.

Further evidence for the importance of focused attention for successful biathlon shooting is provided by a study focusing on gaze control in biathlon (Vickers & Williams, 2007). The authors aimed at scrutinizing changes in visual attention and its relation to shooting performance at five increasing physiological workload levels. In order to do this, they manipulated psychological pressure by pretending that their shooting performance will be used for national team selection. Ten biathletes of the Canadian junior and senior national team absolved a level test on a cycle ergometer with power output levels increasing stepwise from 55%, 70%, 85% and 100% of the athletes' individual maximal oxygen uptake (VO2 max). After baseline measurement under rest conditions, the athletes absolved two shooting blocks including five shots each immediately after every workload level. The shooting task was performed exclusively in standing position and simulated biathlon shooting by applying a laser system, shooting on a single target of 10 mm diameter from five meters distance (Vickers & Williams, 2007). The authors measured cognitive anxiety and cognitive worry for a manipulation check, continuously monitored heart rate during test procedure, determined shooting accuracy and collected gaze behavior. In this regard, the authors focused on the *Quiet Eye* that is defined as "[...] the final fixation or tracking gaze that is located on a specific location or object in the task space within 3° of visual angle (or less) for a minimum of 100 ms." (Vickers, 2016, p.1) and assessed the duration of final fixation (Quiet Eye) by applying an ASL 501 Eye Tracking System. As the initiation of the final movement (in this case: firing the shot) is crucial for determining the Quiet Eye offset, an external camera recorded the trigger finger. Based on several analyses including both group analyses and individual analyses, following results can be noted: First and foremost, mean Quiet Eye duration was longer on hits than on misses at submaximal physiological workload levels (including 55%, 70% and 85% of athletes' maximal individual oxygen uptake). In addition, shooting accuracy decreased with increasing workload level, independent of psychological pressure conditions which, for their part, did not affect heart rate. When focusing on individual results rather than on group based findings, Vickers and Williams (2007) distinguished between seven athletes classified as choking under pressure because of decreased shooting accuracy under high pressure, whereas three athletes did not hit the criteria of choking given that they showed stable or even higher performance under high pressure conditions, especially under high physiological workload. Specifically, increasing their final fixation duration seemed to prevent these athletes from choking under maximal workload and pressure conditions. In conclusion, visual attention and in specific the duration of final fixation may play a crucial role for successful biathlon shooting.

While Vickers and Williams (2007) aimed – among other measurements – at examining performance under pressure in an experimental setting, another study investigated psychological processes by analyzing archival competition data. Lindner (2017) examined 85 World Cup pursuit and 50 mass start events across eleven seasons. More specifically, analysis was focusing on the athletes ranked top ten before the last shooting bout as it aimed at investigating the phenomenon of choking under pressure in top ranked athletes. Findings revealed an increased probability of missing the fifth shot (i.e., final shot) in the last shooting bout for biathletes leading the competition which is linked to choking under pressure. In addition, lower shooting accuracy was associated with increased shooting times. In closing, Lindner (2017) observed a so-called *momentum effect*, displaying a decrease of the probability to miss the final shot when already missing one or more shots in the preceding four shots of the final shooting block.

Psychological Determinants of Biathlon Performance: Methodological Considerations

When interpreting the presented studies focusing on attentional processes in biathlon shooting (Gallicchio et al., 2016; Luchsinger et al., 2016; Vickers & Williams, 2007), some methodological aspects have to be considered: Studies focused exclusively on standing shooting and neglected prone position, examined shooting performance limited to shooting accuracy but did not include shooting time and differed substantially in ecological validity in their biathlon shooting task. While Gallicchio et al. (2016) as well as Vickers and Williams (2007) induced physiological workload on a cycle ergometer, Luchsinger and colleagues (2016) used roller skiing sessions on a treadmill. Similar to Vickers and Williams (2007), Luchsinger et al. (2016) simulated biathlon shooting on a 5 meter shooting range using a laser system whereas participants assessed by Gallicchio et al. (2016) performed actual biathlon shooting on a 50 meter shooting range, firing real ammunition by using their own rifle.

Applying a different methodological approach, Lindner (2017) not only provided novel insights into performance under pressure in biathlon but also demonstrated the potential of archival data not only to examine physiological factors and motor performance in elite biathlon (e.g., Luchsinger et al., 2018; Luchsinger et al., 2019) but also to improve our understanding for psychological factors in biathlon: On the one hand and in contrast to experimental studies, these analyses allow to include a large sample size that is in contrast to experimental research in expertise as small sample sizes and lack of statistical power are an inherent problem in expertise research (McAbee, 2018). On the other hand, theories can be tested by means of actual behavior under real-world conditions and hence ensure highest ecological validity.

1.2.3 Social Determinants of Biathlon Performance

In contrast to biological and psychological factors of biathlon performance, research about the role of social context for biathlon performance is scarce. To the best of my knowledge, only one study (Harb-Wu & Krumer, 2019) examined the impact of social context on biathlon performance so far by investigating the role of supportive vs. non-supportive audience. To this end, the authors analyzed archival data of 155 sprint competitions (World Cup, World Championships and Winter Olympic Games) over a period of 16 years and examined athletes' shooting and skiing performance when competing in their home country, assuming the audience being supportive, compared to when competing abroad (i.e., less supportive audience). Findings indicated that biathletes with the highest expertise level (operationalized as the highest quartile of World Cup ranking points) missed significantly more shots when competing in front of the crowd in their home countries while no effects on skiing performance were observed. In contrast, biathletes ranked in the lower quartile of World Cup points did not show performance decrements in shooting but increased skiing performance (i.e., skied faster at home). Based on these results (Harb-Wu & Krumer, 2019), the type of audience seems to affect both shooting and skiing performance in elite biathletes and is moderated by World Cup ranking.

Next to this lack of previous research, the inclusion of social context information when aiming at understanding, explaining and predicting biathlon performance from an applied perspective seems to be especially relevant due to two main reasons:

First, biathlon represents one of the most famous winter sport in several countries and World Cup events attract more than 100.000 spectators. The audience gets the possibility to be present on both the skiing course and at the shooting range. Consequently, fans react positively or negatively by cheering or groaning on biathletes' performance. As every shooting bout contains five consecutive shots with appr. two seconds interval, the audience even gets the opportunity to evaluate and react to every single shot while the athlete is still performing under time pressure.

Second, as outlined in section 1.1, biathlon comprises different competition formats including both head-to-head and individual competitions. Hence, biathletes experience different social situations during biathlon competitions with both simultaneous shooting with direct opponents when fighting for the win or individual conditions. The role of other competitors gets even more pronounced when focusing exclusively on group competitions such as mass start or pursuit: How does the presence of opponents affect shooting performance compared to when they are shooting alone? Are there differences between shooting face-to-face to one other biathlete compared to shooting in a bigger group of co-acting competitors?

Both of the situations outlined above speak to possible effects through the presence of others (audience or co-competitors). One of the first studies examining the impact of the presence of others on sport performance was carried out by Triplett (1898). He observed that the presence of other co-competing athletes resulted in increased performance in cycling competitions. The effect that the presence of others influences (and typically improves) cognitive or physical performance was subsequently related to the term *social facilitation theory* (Allport, 1924; Zajonc, 1965) and examined by applying different paradigms: During the early stages investigating this phenomenon, research focused especially on co-acting situations while the effect of others being merely present or in the role of an audience has been focused by subsequent studies (e.g., Martens, 1969; Cottrell et al., 1968; Haas & Roberts, 1975). The underpinning mechanisms of social facilitation are primarily attributed to changes in activation level (e.g., *generalized drive hypothesis*: Zajonc, 1965; *evaluation approaches*: Henchy & Glass, 1968; Cottrell et al., 1968; *monitoring model*: Guerin, 1983; *challenge and threat*: Blascovich et al., 1999) or to attentional processes (e.g., *overload hypothesis*: Baron, 1986; *feedback-loop model*: Carver & Scheier, 1981). In addition, the *distraction-conflict hypothesis* (Sanders et al., 1978) represents a bridge between these two directions and assumes both changes in activation level and in attention. However, almost all theories differentiate between simple (or well-learned) tasks and complex (or not well-learned) tasks: While performance tends to improve in the former category through the presence of others, it tends to decrease in the latter task category (Bond & Titus, 1983). This discrimination together with the classification of quantitative (e.g., speed) and qualitative (e.g., accuracy) performance outcomes was transferred to motor tasks in a review by Strauss (2002). Strauss found that performance tends to increase in so-called *conditioning tasks* with demands predominantly on stamina or muscle strength that often represent simple tasks and are measured quantitatively (e.g., running or power tasks). Conversely, the same review suggests *coordination tasks* that rely predominantly on fine motor control such as precision or balance tasks and are often measured qualitatively (Strauss, 2002) are more equivocal including both performance improvements (e.g. Martens, 1969; Haas & Roberts, 1975; Singer, 1965) as well as performance deteriorations (e.g. in goal pursuit task: Martens, 1969; in mirror tracing: Haas & Roberts, 1975; in pursuit rotor task: Butki, 1994).

Based on the outlined task-dependency and the social context of audience and coacting opponents in biathlon competitions mentioned above, it seems reasonable to suggest that social aspects may contribute to our understanding of biathlon performance as well as offering an ideal testbed to examine social facilitation effects.

1.3 A Biopsychosocial Framework to Guide Interdisciplinary Research on Biathlon Performance

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1.3.1 Introduction

Biathlon is a unique combination of two challenging and remarkably different tasks: Cross country skiing in free technique and rifle shooting in either prone or standing position. Over the past few decades, a growing body of biathlon-specific research considerably improved our understanding of the factors determining biathlon performance (for a review, see Laaksonen et al., 2018). This includes biological aspects of biathlon performance, comprising physiological parameters (e.g., Rundell & Bacharach, 1995; Stoeggl et al., 2015; Laaksonen et al., 2020) as well as biomechanical and motor control factors such as postural control, rifle stability, shoulder force, triggering or aiming strategies (e.g., Groslambert et al., 1999; Sattlecker et al., 2014, Baca & Kornfeind, 2012, Köykkä et al., 2020). In addition, another branch of research focusses on psychological factors that influence performance, including the role of attentional processes (e.g., Gallicchio et al., 2016; Luchsinger et al., 2016; Heinrich et al., 2020), dealing with psychological pressure (e.g., Vickers & Williams, 2007; Lindner, 2017) and the effectiveness of psychological interventions (e.g., Groslambert et al., 2003; Laaksonen et al., 2011). However, with only one exception (Harb-Wu & Krumer, 2019), biathlon-specific research has largely overlooked the degree to which social context factors may impact biathlon performance. Here, we advocate a holistic approach to gain a more complete understanding of the factors contributing to biathlon performance. Admitting to the fact that biological determinants, psychological factors and social context never occur in isolation, but instead need to be considered in conjunction, we propose a biopsychosocial framework to guide future research efforts into biathlon performance. This integrative, interdisciplinary and holistic approach to examine biathlon performance is illustrated in Figure 1.

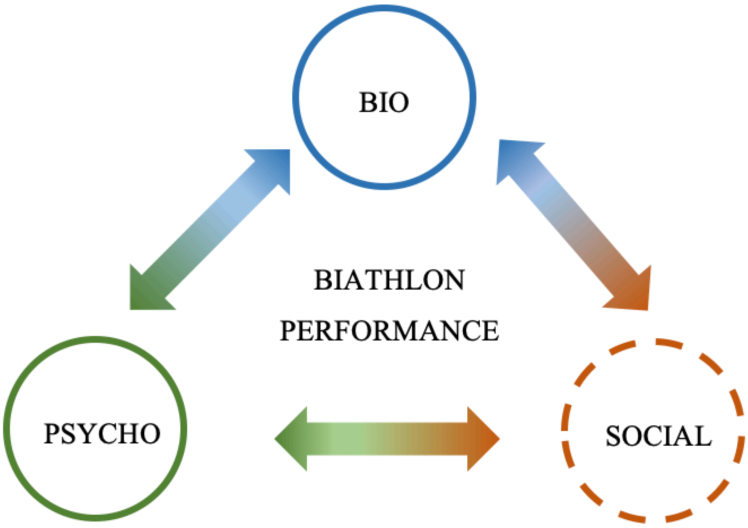

Figure 1. A biopsychosocial framework of biathlon performance

Originally, biopsychosocial approaches were developed in the area of medicine and psychiatry to address limitations of the traditional biomedical model and generally aim at considering behavioral, psychological and social dimensions when trying to understand a person's condition (Engel, 1977; 1997). Nowadays biopsychosocial models have stepped out of their original scope and are widely used, for instance, to explain arousal regulation (Blascovich & Tomaka, 1996) or to examine stress in adolescence (Rith-Najarian et al., 2014). The application of biopsychosocial models in sport is scarce and mainly limited to the field of injuries or pain (e.g., von Rosen et al., 2017; Bumann et al., 2020). Before outlining specific steps that need to be taken to realize a research agenda in biathlon guided by the proposed biopsychosocial framework, we shortly summarize evidence stemming from research focusing on isolated, that is, biological, psychological and social aspects of the framework.

1.3.2 In a Nutshell: Research on Biological Factors of Biathlon Performance

As concerns biological factors, research revealed, for instance, that biathletes with a larger capacity for oxygen uptake (i.e. high peak of oxygen uptake) show faster skiing times (Rundell & Bacharach, 1995; Rundell, 1995). Oxygen uptake at a lactate threshold of 4 mmol/l and gross efficiency may predict high proportions of variance in biathlon competition performance (i.e., the higher, the better; Laaksonen et al., 2020). The capacity for oxygen uptake becomes even more important as rifle carriage in skiing results in higher physiological demands such as increased oxygen costs, greater ventilation and higher lactate values (Frederick, 1987; Rundell & Szmedra, 1998; Jonsson Kårström et al., 2019), in biomechanical adaptations (e.g. higher cycle rate and leg forces; Stoeggl et al., 2015), and in decreased performance in maximal roller skiing compared to roller skiing without a rifle (Jonsson Kårström et al., 2019). Additionally, several motor control parameters (i.e. biomechanical aspects) were shown to be reliable predictors for distinguishing between expert and less skilled biathletes: Expert biathletes are characterized by higher rifle stability (i.e., less rifle sway; Sattlecker et al., 2014; Hoffman et al., 1992; Sattlecker et al., 2017) and show a more stable aiming pattern (Baca & Kornfeind, 2012) as well as higher postural control (Sattlecker et al., 2014; Sattlecker et al., 2017; Groslambert et al., 1999). Furthermore, successful biathlon shooters exhibit higher force values of the rifle stock in the back shoulder and specific triggering patterns characterized by an increasing force followed by a plateau before firing a shot (Sattlecker et al., 2017; Hansen et al., 2019). Successful shots are further characterized by being fired at a specific phase of the cardiac cycle (under exercise conditions less frequently from 100-200 ms after the R-wave; Gallicchio et al., 2019). Dependent on the aiming strategy (so-called *hold* vs. *timing* strategy), shooting accuracy is associated with more stable aiming at the center of the target and a decrease in total velocity of the rifle just before firing the shot (Köykkä et al., 2020). Finally, some research focused on the impact of physiological workload on shooting performance, revealing equivocal findings: Some studies showed deteriorations in shooting accuracy with increasing workload (Hoffman et al., 1992; Grebot et al., 2003; Vickers & Williams, 2007; Ihalainen et al., 2018) while other studies indicate no effects (Gallicchio et al., 2016; Luchsinger et al., 2016; Heinrich et al., 2020).

1.3.3 In a Nutshell: Research on Psychological Factors of Biathlon Performance

Psychological research in biathlon focused on psychological processes (including neurophysiological mechanisms) underpinning successful biathlon shooting as well as psychological interventions that aim at enhancing performance. Concerning the former, for instance, successful biathlon shooting is related to higher frontal theta power (an electroencephalographic measure), which itself is associated with attentional monitoring processes (Gallicchio et al., 2016; Luchsinger et al., 2016). The importance of focused attention was corroborated by Vickers and Williams (2007) providing evidence that longer final fixations relate to higher shooting accuracies under different psychological (i.e., low versus high) pressure situations (for contradictory findings, see Heinrich et al., 2020). Also research based on archival competition data revealed that dealing with pressure may be crucial to successful performance. Lindner (2017) showed that the likelihood of missing the final shot of the final shooting bout turns out to be significantly higher when compared to the previous shots of the final bout, especially in top ranked biathletes. Furthermore, longer shooting times are often resulting in performance deteriorations (see Lindner, 2017). Additionally, psychological interventions such as autogenic, imagery or relaxation training combined with specific shooting training tend to enhance shooting accuracy (Laaksonen et al., 2011) and rifle stability (Groslambert et al., 2003). Finally, a recent prospective study showed that dispositional mindfulness (i.e., awareness, refocusing etc.) might also predict proportions of the variance in shooting performance in advanced biathletes (Josefsson et al., 2020).

1.3.4 In a Nutshell: Research on Social Context Factors of Biathlon Performance

In contrast to biological and psychological factors, our knowledge about the role of social context for biathlon performance is very limited. Based on archival competition data, Harb-Wu and Krumer (2019) recently examined audience effects by comparing athletes' shooting and skiing performance when competing abroad vs. in their home country (supportive audience). While biathletes with the highest expertise level missed significantly more shots when competing in front of a supportive audience, lower-ranked biathletes did not show performance decrements in shooting but increased skiing performance (i.e. skied faster at home).

1.3.5 Interim Summary

First, research in biathlon is mainly focusing on biological and psychological determinants in isolation rather than examining these factors in conjunction. Second, the impact of social context has largely been neglected thus far. To ultimately realize a more integrative and interdisciplinary research approach towards biathlon performance under the umbrella of a biopsychosocial framework (see Figure 1), we propose that (at least) three steps need to be taken.

1.3.6 Step 1: Studying Social Context

As highlighted by the dashed lines surrounding the 'social' context in Figure 1, more research addressing the impact of social context on biathlon performance is mandatory. First, the impact of the presence of audience – regardless of the type of audience (see Harb-Wu & Krumer, 2019) – on both skiing and shooting performance has not been examined yet. Second, the only study on social context thus far is based on archival competition data, experimental research, however, is lacking. For instance, given that research on social presence has shown that individuals characterized by extraversion and high self-esteem tend to show performance improvements through the presence of others while individuals characterized by neuroticism and low self-esteem tend to show performance impairments (Uziel, 2007; Graydon & Murphy, 1995), an experimental approach could serve to examine how athletes' personality characteristics interact with the presence vs. absence of an audience in biathlon. Third, if social context matters, then the question arises *if* and *how* the presence vs. absence of direct opponents – be it at the shooting range or on the skiing course – affect biathlon performance. While all biathletes start at the same time in mass start competitions or with a delay based on the result of a previous race (typically sprint) in pursuit, the position on the skiing course always corresponds to an athlete's overall ranking and competitors are faced with their direct opponents on both the skiing course and the shooting range. It is hence conceivable that the number of simultaneously shooting biathletes may affect performance in head-to-head competitions. Finally, social context in form of a familiar vs. unfamiliar environments or cultures may likewise affect competition performance in biathlon. For instance, the next Winter Olympics will take place in China while Italy will host the Winter Olympics in 2026.

1.3.7 Step 2: Building Interdisciplinary Bridges

From a biopsychosocial framework perspective, a truly interdisciplinary approach that allows to concomitantly examine biathlon performance from different viewing angles goes beyond looking at relevant factors in isolation. There are initial attempts taking, for example, a biopsychological approach. For instance, studies examining the role of focused attention by means of measuring electroencephalographic activity also considered biological factors by manipulating cardiovascular load immediately before assessing shooting performance. Results on this particular question are somewhat mixed by showing decreased frontal theta power on the one hand (Gallicchio et al., 2016) or the lack of an effect on the other hand (Luchsinger et al., 2016). Vickers and Williams (2007) also showed a significant decrease of the duration of the final fixation with increasing physiological workload. By contrast, Heinrich et al. (2020) did not find an effect of physiological workload on fixation durations. Next to biopsychological research, Harb-Wu and Krumer (2019) examined initial biosocial links when showing negative effects of social context on top-ranked biathletes' shooting accuracy as well as positive effects on low-ranked biathletes' skiing performance (representing biological factors). In conclusion, more interdisciplinary approaches are needed to unravel the intricate links between biological, psychological and social factors determining biathlon performance. Consequently, these approaches offer new opportunities to resolve, for instance, equivocal findings regarding the impact of physiological workload on shooting performance by integrating psychological factors and social context potentially affecting biological factors.

1.3.8 Step 3: Taking a Big Data Approach

Our final suggestion is to consider taking a big data approach to explain and predict biathlon performance. Big data approaches are still in their infancy as far as the sport sciences are concerned. Such an approach is, for instance, used for tactical analyses in professional soccer (e.g., Rein & Memmert, 2016). Besides characteristics such as featuring a high volume of data that is produced at high velocity, big data is defined by a diverse set of data and the aim to capture entire populations or systems (n=all, Kitchin, 2014). Transferred to biathlon, this approach may bring together physiological and biomechanical data from training and competition, psychological factors such as personality characteristics (i.e. traits) or aspects displaying relevant psychological states (e.g., stress and recovery, perceived pressure) as well as social context information at the skiing course and the shooting range (e.g. audience, opponents) in one database. Both external and internal (i.e. individual) factors could be considered by combining multi-methodologically gathered data (e.g., self-reports, tracking data, physiological monitoring, competition protocols). However, this approach not only requires cross-disciplinary collaborations, but also that researchers and practitioners are sensitive to ethical considerations and privacy issues – challenges that are generally associated with big data (Boyd & Crawford, 2012; Spaaij & Thiel, 2017). Despite these challenges, we are convinced that a big data approach is timely and viable to contribute to our understanding of biathlon performance in a truly interdisciplinary and holistic manner as proposed by the biopsychosocial framework.

2 Building Interdisciplinary Bridges in Elite Biathlon Research

2.1 Research Questions and Work Program

With the aim of understanding, explaining and predicting biathlon performance, biological determinants as well as psychological aspects have been in the focus of scientific research in the past and have mostly been examined in isolation rather than in conjunction. In addition, the complex sport of biathlon includes social context that has mostly been neglected in research so far. Consequently, the aim of the dissertation project is twofold:

On the one hand, I aim at contributing to the current understanding of biathlon performance by building interdisciplinary bridges and applying a holistic approach that focuses on psychobiological determinants in conjunction rather than in isolation. Given that psychobiological research in biathlon is scarce and additionally characterized by both equivocal findings and large methodological heterogeneity, the first study of this dissertation project examines biological and psychological determinants in conjunction (see blue-green arrow in Figure 1) by focusing on the role of gaze behavior, thereby conceptually replicating the only study looking at the role of gaze in biathlon thus far (Vickers & Williams, 2007) in a setting of high ecological validity (Chapter 3.1).

On the other hand, I strive to fill the dashed line representing the lack of research in the social part of the framework (see Chapter 1.3, Figure 1) by again applying an interdisciplinary approach that includes both biological factors and social context of biathlon performance. To this end, Study 2 and Study 3 examine the impact of social context on elite athletes' biathlon performance by specifically focusing on the presence vs. absence of audience (Chapter 4.1) as well as the role of co-competitors at the shooting range (Chapter 4.2). In addition, the study presented in Chapter 4.2 takes a big data approach, thereby corresponding to the call for step 3 in Heinrich et al. (2021; Chapter 1.3).

Consequently, the current thesis addresses the steps we are suggesting in Chapter 1.2, namely *Looking at different factors in conjunction* in three empirical studies (Chapter 3.1, Chapter 4.1 and 4.2)*, Integrating social context* (Chapter 4.1 and 4.2), and finally *Taking a big data approach* (Chapter 4.2).

2.2 Methodological Considerations

First and foremost, the empirical work of this thesis is based on methodological considerations concerning ecological validity and representative task design as well as the aim to conduct research in biathlon experts. In addition, as the first study representing a psychobiological approach to understand biathlon performance is particularly focusing on gaze behavior in biathlon, it turned out to be necessary to develop and validate a tool to measure gaze behavior specifically in biathlon that is presented in Chapter 2.3 before leading to the empirical studies building the core of this thesis.

With the aim of contributing to our knowledge about biathlon performance at high performance level, the inclusion of a high expertise sample represents a central part of the present work. Hence, I examined on the one hand elite athletes who represent the German national senior team and, in order to have the opportunity for testing expertise differences, I additionally included sub-elite athletes representing the German national junior team (Study 1; Chapter 3.1). On the other hand, I included international athletes participating in World Cup competitions by analyzing archival competition data (see methodological approaches below). While Study 2 is focusing on a subset of athletes meeting specific criteria (Chapter 4.1), Study 3 includes all athletes participating in mass start and pursuit World Cup events between the years 2005 and 2020 and is consequently based on big data analyses (Chapter 4.2).

Furthermore, as biathlon performance represents the central part of the present work, I aimed at including both tasks of biathlon in the presented research, that is skiing and rifle shooting. In contrast to several previous studies, both prone and standing shooting as well as shooting accuracy and shooting time are considered. In addition, I pursue an interdisciplinary approach to contribute to our knowledge about biathlon performance. As a result, I focus on biological and psychological determinants (Study 1) and biological factors and social context (Study 2 & 3) in conjunction. Especially in the first study, the interdisciplinary approach implies a complex study design by measuring various physiological data, collecting detailed shooting performance data and assessing gaze behavior using an eye tracking technology developed for this purpose. Detailed information about the tailored eye tracking system is provided in Chapter 2.3. Finally, I aimed at high ecological validity and representative designs in the empirical work. Hence, I opted to examine the original tasks of biathlon (real shooting with real ammunition by using the individual rifle) and the task that requires the same demands as skiing but enables higher controllability, respectively (roller skiing on a treadmill) in Study 1. In Study 2 and Study 3 I analyzed archival competition data that provide highest ecological validity by displaying real behavior in real World Cup competitions. As small sample size and consequently low statistical power is an inherent problem of expertise research (McAbee, 2018), these studies allow us to capture all biathlon experts that are available and hence work around this issue.

2.3 Developing and Validating a Tool to Measure Gaze Behavior in Biathlon

Chapter 2.3 was published as:

Hansen, D. W., Heinrich, A., & Cañal-Bruland, R. (2019). Aiming for the quiet eye in biathlon. In *Proceedings of the Symposium on Eye Tracking Research and Applications* (ETRA '19; article No. 10; 7 pages). ACM, New York, NY, USA. https://doi.org/10.1145/3314111.3319850

Abstract

The duration of the so-called "Quiet Eye" (QE) – the final fixation before the initiation of a critical movement – seems to be linked to better perceptual-motor performances in various domains. For instance, experts show longer QE durations when compared to their less skilled counterparts. The aim of this paper was to replicate and extend previous work on the QE (Vickers & Williams, 2007) in elite biathletes in an ecologically valid environment. Specifically, we tested whether longer QE durations result in higher shooting accuracy. To this end, we developed a gun-mounted eye tracker as a means to obtain reliable gaze data without interfering with the athletes' performance routines. During regular training protocols we collected gaze and performance data of 9 members (age 19.8 ± 0.45) of the German national junior team. The results did not show a significant effect of QE duration on shooting performance. Based on our findings, we critically discuss various conceptual as well as methodological issues with the QE literature that need to be aligned in future research to resolve current inconsistencies.

2.3.1 Introduction

The aim of this paper is to investigate the Quiet Eye (QE) hypothesis in elite biathletes and to replicate and extend on the previous work on QE in biathlon (Vickers & Williams, 2007).

The question of why some people are more skilled in complex domains than other people has long been debated. It is specifically pronounced in high-performance sports where marginal advantages can make the difference between winning or loosing (e.g., getting a medal or breaking a record). Optimal performance may require that the athlete is capable of picking up the right information at the right time and then take action as swiftly and accurately as possible. Various interacting systems are involved in the visual control of action the motor system and the visual system (Land & Tatler, 2009). Temporal and spatial relationships between gaze fixations and motor action are seen as a key factor for performance (Mann et al., 2007). In many sports, the duration of the final fixation before initiating the critical movement, the so called Quiet Eye (Vickers, 1996b) is seen as a measure for perceptual-cognitive expertise, even though the cognitive mechanisms underlying the QE hypothesis are not fully understood.

Gaze information can potentially yield important insights into human performance, and in turn, enhance elite athletes' performance. To this end, eye tracking has become important in identifying elite athletes' eye movement patterns (Williams et al., 2002; Klostermann et al., 2013; Vickers, 1996b; Vickers & Williams, 2007). Eye tracking is the process of monitoring eye movements for the purpose of analyzing the eye movement patterns relative to the head or determining the point of gaze. Eye tracking is an active multidisciplinary research field, which has shown great progress in the last decades in a range of domains including Medicine, Marketing, Psychology and Human factors (Duchowski, 2007). Several experiments have investigated performance of athletes by e.g., identifying differences between novices and experts or training novices based on knowledge of eye movements from experts (Alfonso et al., 2012; Hayhoe et al., 2012; Hüttermann et al., 2013; Mann et al., 2013; Paeglis et al., 2011; Pires et al., 2013; Pluijms et al., 2015).

2.3.2 Biathlon

Biathlon is a winter sport which combines cross country skiing with rifle shooting. The athletes have to complete a given distance on skis while carrying their rifle (the minimum weight of the rifle is 3.5 kg). The total skiing distance is divided into either two or four shooting rounds on targets at a distance of 50 meters. Half of the shootings are performed in prone position, the other half in standing position. The size of the shooting targets are 4.5 cm in the prone position and 11.5 cm in the standing position, reflecting that postural control and hence keeping the rifle stable is harder in the standing condition. Each shooting round consist of five shots at five circular targets. Misses are penalized. The overall performance is determined by skiing time, shooting accuracy and time at the range. The biathletes are looking through the diopter while trying to bring the rifle in a position where the ring of the global sight and the focused target overlap as much as possible (Baca & Kornfeind, 2012). It is held that athletes either follow a precision strategy (i.e., the rifle is kept as stable as possible in the center of the target before shooting) or a reaction strategy (i.e., they shoot as soon as the target travels through the center of the diopter). Both strategies seem to be applied independent of the postural condition. Examining the relationship between gaze control (including QE) and shooting performance is therefore of utmost importance to provide athletes and coaches with evidence-based recommendations regarding performance and training. Section 2 presents related work and in particular introduces the QE hypothesis and its relevance to the present experiments. Section 3 presents the experimental setup and arguments of designing QE experiments in an ecologically valid setting. In Section 4 we propose a rifle-mounted eye tracker that is intended for measuring eye movements on biathletes. The main findings are presented in Section 6 and further discussed in Section 7.

2.3.3 Motivation

Gaze behavior in sports has predominantly been studied in terms of location, duration, and fixation frequency. Initial scientific effort on gaze behavior reveals that experts use fewer fixations, of longer durations than non-experts across a wide range of sports (Mann et al., 2007; Nieuwenhuys et al., 2008). Several studies indicate that the gaze behavior prior to an action is an important performance factor e.g., that the fixation duration of elite performers is significantly longer than that of less skilled performers, suggesting that those who consistently achieve high levels of performance have learned to fixate or track critical objects or locations for earlier and longer durations (Vickers, 2016). The Quiet Eye is a popular hypothesis that relates fixation duration to performance (Vickers, 1992). An overview of the QE hypothesis is provided in Vickers (2016). The definition of Quiet Eye varies between studies, but in this paper we will refer to the definition used by Vickers (1992) "the final fixation that is located on a specific location or object in the visuo-motor workspace within 3° of visual angle for a minimum of 100 ms". Vickers and Williams (2007) suggest that task-relevant environmental cues are processed, and motor programs are retrieved and coordinated for the successful completion of the task during the QE period (Vickers, 1996a; Vickers, 1996b). In several types of aiming tasks, such as rifle shooting, basketball and golf, studies have found that experts had longer QE periods and more pronounced hemispheric asymmetry than non-experts (Janelle et al., 2000; Vickers, 1992; Vickers & Lewinski, 2012). While the validity of the QE hypothesis is confirmed by several studies the underlying processes are not fully understood. Studies in which the task demands have been manipulated reveal that more complex tasks required longer QE durations and only under a high information-processing load was QE beneficial (Williams et al., 2002; Klostermann et al., 2013). Studies on for example dart and bowling did not confirm QE hypothesis (Chia et al., 2017; Rienhoff et al., 2012).

QE was shown in biathlon (Vickers & Williams, 2007), but (1) QE is not explicitly related to fatigue, the obvious time pressure for the athletes nor the fact that keeping the eyes open for longer dries the eyes. (2) The criterion of 3◦ of visual angle within a foveated object is a rather large quantity especially in aiming tasks where the foveated object is typically much smaller than 3◦. It is also a bit unclear why 3◦ is the critical value; (3) The critical action in biathlon may be interpreted as when the trigger is pushed but within biathlon the entire trigger action constitutes several critical steps. In other words, what is the critical action in a sequence of unfolding actions in this case?

2.3.4 Experimental Setup

The purpose of the experiment is to scrutinize the QE hypothesis and to evaluate whether it is a reliable measure that can be used for training expert biathletes.

Participants

5 men and 4 female athletes age 19.8 ± 0.45 from the German junior biathlon national team participated in the experiments. The athletes are expert shooters and are all competing at national and international levels.

Location

The experiments were conducted in an indoor shooting range at a biathlon training center in Germany. The training center is used both for training and conducting performance tests. On the 50 meters range the athletes can use live munition on biathlon competition targets. Directly connected to the shooting range is an indoor sports laboratory containing a treadmill for roller skiing (about 20 meters apart).

Equipment

The gaze behavior was assessed with an eye tracker tailored for this purpose (shown in Figure 2). The reasons and design criteria for the eye tracker are further discussed in section 4. For power supply and data transfer, the eye tracker was connected via USB to a MacBook Pro. The frame rate of eye tracker is 60 fps. A Piezo electric force sensor (> 200 samples/s) synchronized with the eye tracker and connected to a micro controller has been made and used to measure the force put on the trigger. The sensor data is transferred to the computer via a serial connection. A Scatt (Scatt, 2019) shooting system (weight 30 g) was mounted at the rifle's barrel and connected to a PC. The system provides, after initial calibration, detailed information about shooting performance such as radial error within the target (e.g., not only hit and miss) and the movement of the rifle relative to the target before the shot. It can be used under live firing conditions on actual biathlon targets. The Scatt system does not allow for frame-based synchronization with the eye tracker and is used in these experiments for determining where the gun is pointing and gaze is directed.

Performance Tests

The eye tracking experiment was conducted as part of a standardized performance test. The performance test involves roller skiing on a treadmill at four increasing intensity levels and shooting series of five shots after every intensity level. The intensity level is specified by treadmill slant angles (set at 1,3,6 and 0 degrees). Each level lasts 6 minutes. Immediately after each level, the athlete had to continue with roller skis to the shooting range where the athlete's rifle was located. The athlete made a standard 5 shot sequence in either prone or standing position and returned to the treadmill where the next level started.

2.3.5 The Need for a Tailored Eye Tracker

Commercial eye trackers are either remote, tower mounted or mobile / head mounted (Hansen & Ji, 2009). Eye trackers need calibration to give accurate gaze estimates. Typical eye trackers yield accuracies from 0.5-1.5 degrees measured on the screen in remote eye trackers or in the scene image when using mobile eye trackers. However, user calibration is a bit time consuming and the accuracy of eye trackers are typically influenced by changes in head position and especially with depth changes e.g., when leaving and returning to the eye tracker (Hansen & Ji, 2009).

A pre-study revealed that standard eye trackers would be unsuitable for experiments with biathlon. Some arguments are: (i) To obtain unbiased results it is important to minimize how much the eye tracking equipment, calibration and test procedures influence the existing procedures. Each athlete needs to be able to use their own rifle. Each rifle is customized to the athlete and hence the morphology of the rifles and how the athlete place the head relative to diopter impose significant variability. The eye tracker consequently needs to be as compact and adaptable as possible. (ii) Research on performance analysis of athletes is typically conducted using a mobile eye tracker, but in biathlon it would be inconvenient for the athletes to wear a mobile eye tracker while skiing and shooting. It would be unacceptable to stop the tests between skiing and shooting to change equipment. (iii) Existing remote eye trackers are typically too wide and would interfere with other equipment if mounted on the rifle. (iv) When using eye tracking glasses the athletes would typically look upwards or even over the frames. This means that there could be significant data loss due to missed eye detections. Beside, the frames of the mobile eye trackers would typically interfere with the athletes' line of sight hence interrupting the normal procedures. (v) The procedure for how calibration should be done when the eye tracker is placed on the rifle is unclear. (vi) Calibration seems to be needless for these experiments since even with a good calibration there are, to our knowledge, no gaze estimation methods which yield sufficiently accurate estimates of gaze to determine where (through the diopter) the athlete is looking. (vii) Gaze estimation errors occur in head mounted eye trackers as a consequence of parallax; that is when the distances of the athlete-to-calibration-targets and athlete-to-gazed-objects during experiments are different (Mardanbegi & Hansen, 2012; Narcizo & Hansen, 2015). Even with a good initial calibration the athletes' head position change between standing and prone shootings. Parallax errors will therefore occur thus influencing the calibration accuracy even more. (viii) It is sufficient to have a reference point to indicate whether or not the athletes are looking though the diopter as (1) the QE only describes the duration on the final target (here only through the diopter) (2) it is fair to assume the target is not observable by an eye tracker. In other words, calibration would be needless in this case.

Diopter-mounted eye tracker

The eye tracker developed for these experiments is designed to be mounted directly on the diopter and can easily be switched between rifles. The athlete is therefore not significantly disturbed by the equipment. The IR sensitive USB camera (60 fps) can be reoriented as to account for different head positions and anthropomorphic difference of the athletes as well as the physical constraints of the individual rifle. A set of LEDs is placed concentrically around the diopter to illuminate the eye and make corneal reflections. The weight of the eye tracker is about 40 grams and hence when mounted on the diopter of the rifle it will not generally not influence the athletes.

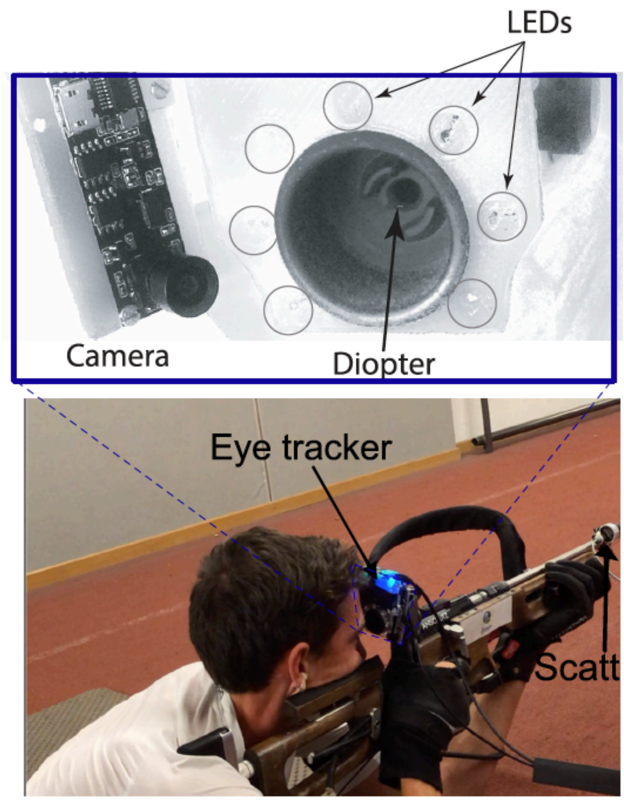

Figure 2. The diopter-mounted eye tracker used in the experiments. (Top) details of LED and camera (Bottom) Mounting of the eye tracker on the rifle.

Eye Tracking

A statistically learned model was applied to identify the pupil and visible glints in each image (Hansen et al., 2014; Hansen et al., 2002). Despite the camera was placed relatively close to eye, the variable light conditions, shadows from the diopter and variable viewing angles complicated the analysis. The number of glints visible in the images also varied as a function of head pose relative to the diopter and camera pose. The virtual glint (*VG*) is defined as the mean of the stable glint centers. Stable means those glints that can be consistently detected during a shooting (Hansen et al., 2014). The difference between *VG* and the pupil center, p_c, indicates how close the athlete is looking towards the diopter. There will typically be an offset between the pupil and *VG* due to (1) the angle kappa (difference between optical and visual axes), (2) viewing angle; (3) distance between light source and eye; (4) the spatial offset between the corneal reflection and the pupil (Hansen & Ji, 2009).

It makes sense to use the *VG* as the relative measure of gaze on the "object" since (1) even with a good calibration the eye trackers would be insufficiently accurate compared to the size of the hole in the diopterhole; (2) the definition of QE is only concerned with the final fixation on the object, which in turn is measured through the diopter; (3) the angle kappa is fixed for an individual hence only imposing a (relatively) stable offset between *VG* and the center of the pupil. Under these fair assumptions it is easy to integrate calibration free QE investigations into the normal training and test procedures used by the athletes and coaches.

Without calibration it is clearly not possible to know exactly where the person is looking (Hansen & Ji, 2009). However, provided the distance between pupil and *VG* is small (due to angle kappa and viewing angle) and stable, it is likely (in this setup), that the person is looking through the diopter. This assumption is more strict than the 3 degrees used in the definition of QE.

Notice that the Scatt system indirectly provides a measure of the gaze on the target as (1) the athlete is looking at the target through the diopter; (2) the relative orientation of the rifle, diopter and the Scatt system was calibrated prior to use.

2.3.6 Data Analysis

The video and trigger data was manually annotated using an annotation tool developed for these experiments. The tool synchronizes video, eye tracker and trigger data and allows the annotator to make single frame annotations.

The start of the sequence is defined at the point in time where the chin touches the rifle for the first time while the end is defined when the cheek leaves the rifle after the last shoot. Similarly the onset and the offset of the final fixation as well as for the onset and offset of blinks and shoot rebounds were manually annotated. The synchronization of the trigger data and the video allowed the detection of the final movement that initiated the shot. For the athletes there is much involved in delivering an ideal shot. As shown in row 4 of Figure 4, the athletes strive towards an ideal trigger force curve. First they try to achieve a plateau at 70 – 80 percent of the total force leading to a shot and then make the final pressure on the trigger. In line with Vickers and Williams (2007) the QE duration is defined as the final fixation before the initiation of the final action. This means that the QE is to be measured from an initial fixation until the rifle is fired.

The athlete may momentarily loose focus of the target e.g., due to eye blinks and gun motion and hence a refixation of the target is needed. Here we define the *final action* as the peak of trigger force that leads to the shot. *Fixation duration* is defined as the interval where the eye remains stable and uninterrupted by eye blinks, head movements or eye movements. Blinks, shoot rebounds and eye movements were manually identified and annotated. The onset of the final fixation is identified by backtracking from the shoot. The duration of the final fixation was calculated (in seconds) for every shot based on the number of frames between the start and stop of a fixation multiplied by the sampling rate (60 Hz).

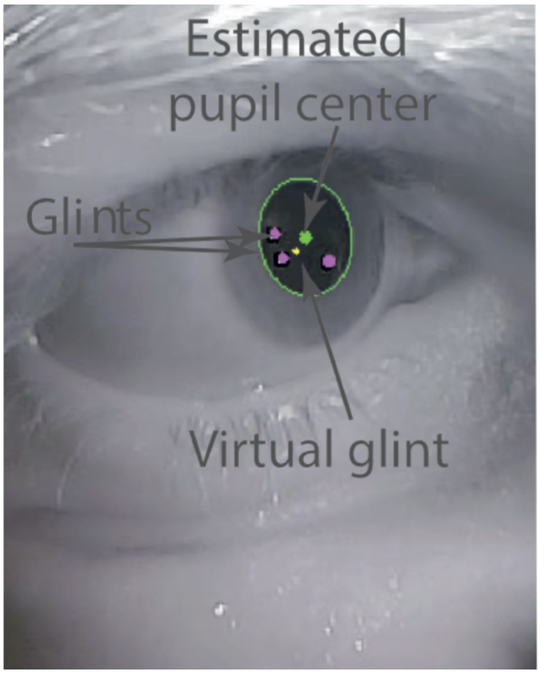

Figure 3. A single frame from a shooting with the pupil estimate (green), reflections (red) and the virtual glint (*VG;* yellow).

2.3.7 Observations

Eye Movements

This section presents the main findings of these experiments. Figure 4 shows the eye tracking data of a single shooting sequence. The pupil centers and the reference points have been normalized to zero mean for display purposes. The fairly constant and relative short distance of the pupil centers and the virtual glints (*VG*), displayed in the first three rows of the figure, shows that the athlete is looking through the diopter quite consistently from the start. There is a bit of head movements e.g., after a shot has been fired. In this example the athlete makes Vistibulo Ocular Reflexes (VoR) to maintain focus through the diopter. In fact, by comparing the trigger data with the eye movement data it is evident that there are so little eye movements that the recoil from the shot can be seen in the eye data. In these experiments the effect of recoil is quite low since it is expert shooters participating in the experiment. As shown in Figure 4, the Kernel Density Estimate of the relative positions of the pupil and *VG* measured in consecutive frames (> 40.000) in all video frames indicate that, eye movements are rare and small during a shooting session but larger eye movements occur with low probability.

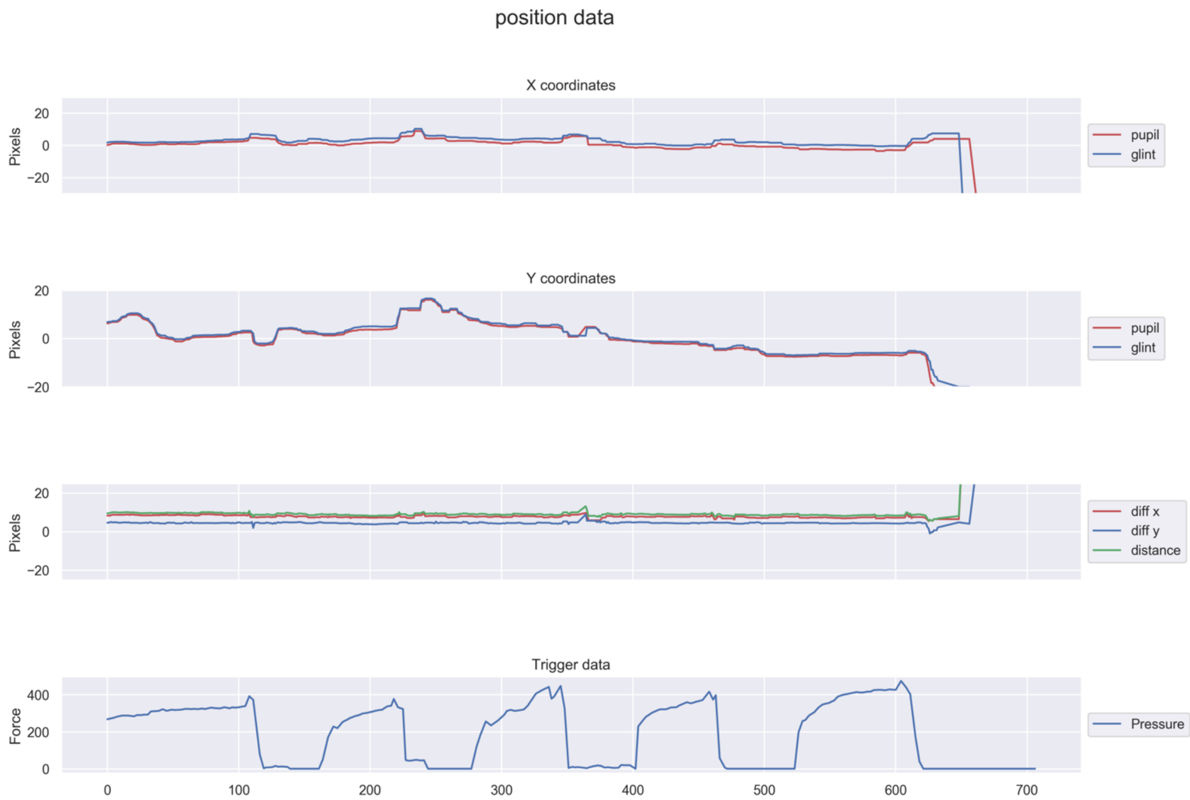

Figure 4. A sequence of 5 shootings of a single athlete. The two top rows show the center of pupil (red) and virtual glint, VG (blue) for the x and y coordinates, respectively. Row 3 shows the difference between V G and pupil center in x and y coordinates. Row 4 shows the trigger force over time. Notice the trigger force cycle: initial pressure, plateau, final force (to fire) and release.

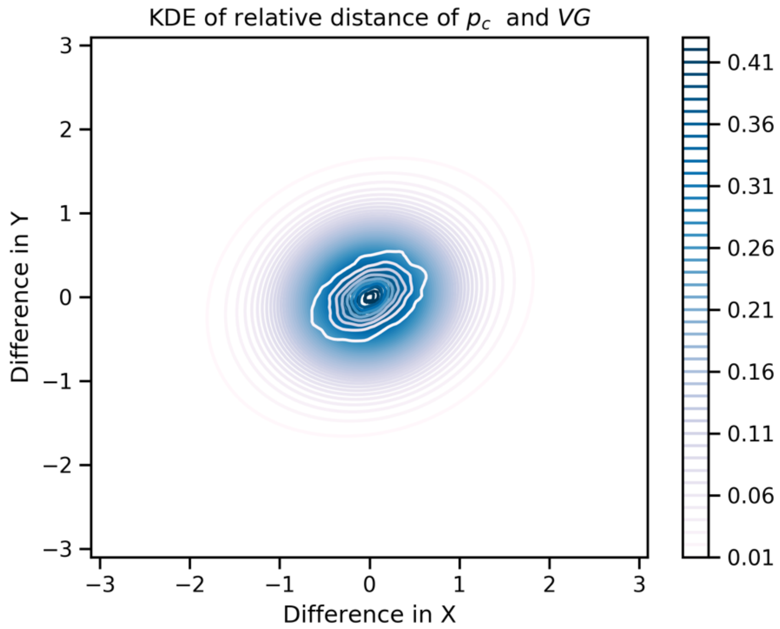

Figure 5. Kernel density estimate of the difference of the pupil and VG in consecutive frames. The distribution is centered around the origin and with only very few large changes.

The paper investigates whether QE is related to performance e.g., whether fixation duration influences hit and miss rates. Figure 6 shows the distributions of the fixation duration conditioned on hit, miss and their combined distribution. The investigations of fixation duration on hit/miss rates naturally induces a binomial distribution.

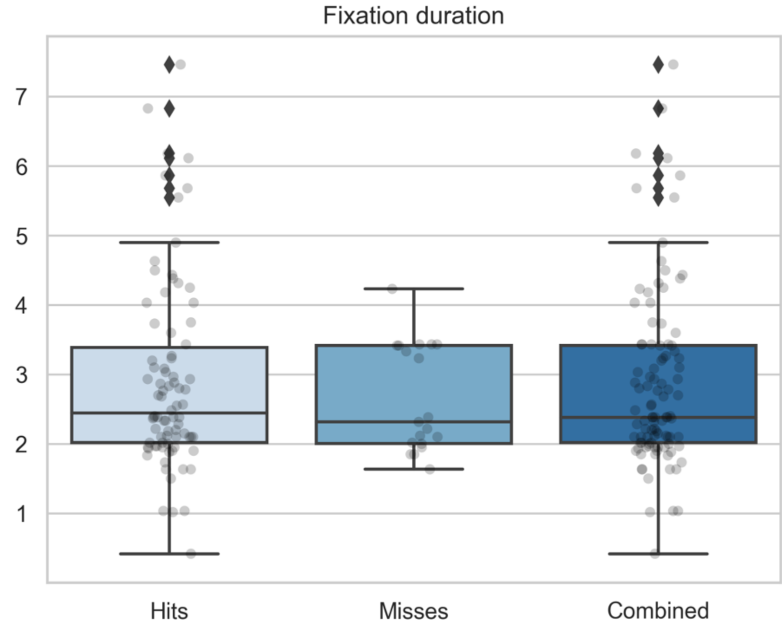

Figure 6. Boxplot of fixation durations as a function intensity level.

The generalized linear model (GLM) is a generalization of ordinary linear regression (e.g., ANOVA) that allows for response variables from the exponential family e.g., binomial distributions (McCullagh & Nelder, 1989). The figure shows, the somewhat expected result for elite shooters, that there are significantly more hits than misses. As there are no observations of misses with a long duration it may at first appear as if the athletes always hit the target with a long duration (e.g., QE). This misleading observation is caused by the highly unbalanced distributions of hits and misses. In fact, the analysis of these distributions under a binomial GLM did not confirm that the two distributions are the same. In other words the results indicate that fixation duration did not influence hit/miss rates (p=0.687) and thus no apparent influence of QE for elite biathletes.

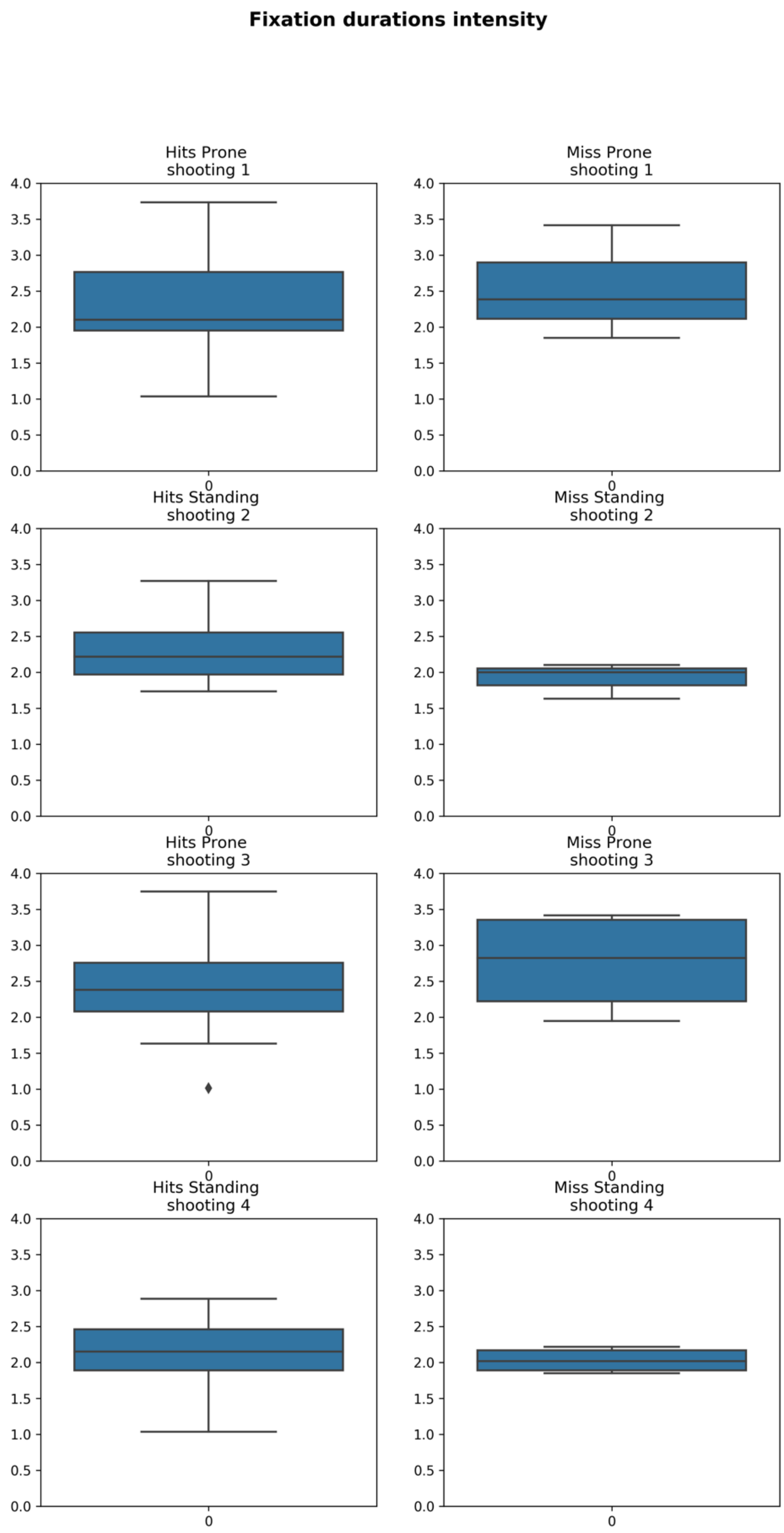

Figure 7. Boxplot of fixation duration as a function of (top) hits (bottom) misses and conditioned on intensity level (increasing left to right).

Figure 7 shows a boxplot of the fixation duration for hit /misses conditioned on the work intensity levels and in prone / standing positions. The results of a binomial GLM analysis yields p-values P = [0.033, 0.256, 0.058, 0.341] where p_i is the p-value for work intensity i. The p-values in prone positions are generally lower than in standing positions. The experiments did generally not confirm QE but when athletes are in low work intensity and in prone conditions QE seems to have an effect.

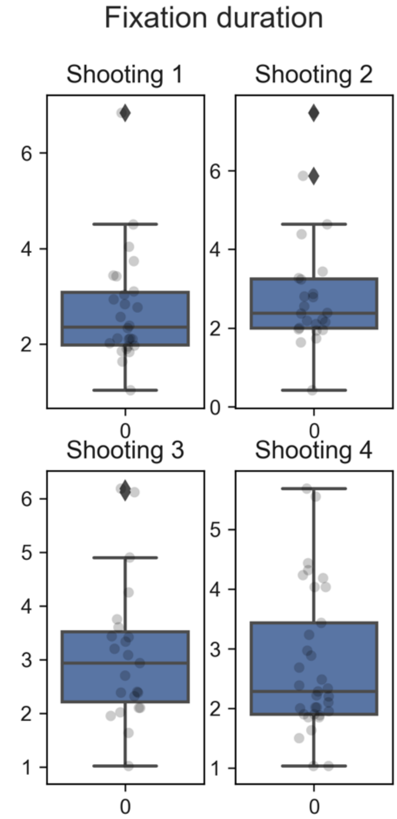

Figure 8. Boxplot of fixation duration as a function of intensity levels.

Figure 8 shows the fixation duration conditioned intensity level. Overall the athletes had a shooting hit rate of $\mu = 0.81$, $\sigma = 0.15$ and fixation times (sec) $\mu = 2.86$, $\sigma = 1.61$. The figure shows that the median fixation duration remains similar despite intensity however the variance increases as a function of the intensity.

2.3.8 Discussion

This paper investigated QE on elite biathletes in an ecologically valid setting. An eye tracker was developed to accommodate limitations of existing eye trackers.

While the athletes are typically keeping their gaze through the diopter and the eyes very still, these experiments do generally not support previous findings for aiming in biathlon tasks (e.g., Vickers & Williams, 2007) but we found support of QE in low workload cases and where athletes were in prone position. This result is somewhat different from the previous findings of Klostermann et al. (2013). The evidence for training QE is generally equivocal for biathlon and it requires more sophisticated longitudinal designs to demonstrate retention. Figure 8 indicates that the athletes may have a rather stable shooting rhythm but that this is slightly but insignificantly influenced by the intensity level. These are expected signs of elite performers; they perform consistently and robustly to trained conditions. We believe that there are several reasons for the discrepancy to previous work:

1) The experiments were conducted as part of a standardized performance test that is known by the athletes. The equipment did not need calibration or re-quired the athletes to wear the eye tracker and hence this study was based on an eco- logically valid setup that did not influence the standardized test or the athletes in any significant way.
2) The eye tracker used in this experiment was made to work on the rifle and without calibration. Without calibration disturbing the experiment, we also avoided parallax errors and erroneous gaze estimates.
3) Vickers and Williams (2007) recorded the movement of the trigger move-ment with an external camera and defined "QE as the final fixation that was maintained on any part of the target for more than 100 ms before and after the trigger pull". This definition is uncertain to when the "final" action is measured: before building the trigger force, during the plateau or at the final pull? In this paper we differentiated the stages of the trigger force and defined the final fixation as the final fixation before the last trigger pull that initiates the shot.

While the fixation duration has an influence on human performance (e.g., for perception), the current definition may be insufficient in fully describing the observations.

1) Drying eyes and blinking interrupt the fixation. When shooting with real ammunition it is common (also for elite athletes) to blink during or even before the shot. Our data even shows cases where athletes blink before or during the shot and still hit the target. Hence more intricate models may be needed to fully describe the observations.
2) The criterion of a final fixation within 3 degrees in the definition of QE seems to be an unwarranted condition biathlon.

The large variance of fixation durations indicates (Figure 6) that there could be many factors influencing the outcome of the shooting beyond fixation duration. The results may have practical importance for daily training; Fixation duration is clearly important for the athletes to perceive the target but the results show that further studies are needed to better understand QE and the other factors that influence performance in biathlon. We speculate that dynamic properties of hand-eye coordination, blinks, and shoot rebounds could have some significance to QE.

3 Building Biopsychological Bridges

After outlining the aim of the present work, providing methodological considerations as well as giving insights into the eye tracking system developed for gaze measurements in biathlon, I will now build interdisciplinary bridges and present the first empirical study of this doctoral thesis. In this study, the co-authors and I focused on biological and psychological determinants of biathlon performance in conjunction (see Chapter 1.3, Figure 1) by examining both the impact of physiological workload and gaze behavior on biathlon shooting performance, thereby conceptually replicating previous work (Vickers & Williams, 2007) in a setting of high ecological validity.

3.1 The Impact of Physiological Fatigue and Gaze Behavior on Shooting Performance in Expert Biathletes

Chapter 3.1 was published as:

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Abstract

Objectives: Biathlon is a discipline that combines cross country skiing with rifle shooting. It demands high shooting accuracy and fast shooting times under increasing levels of physiological fatigue. Building on Vickers and Williams (2007), the current study aimed at scrutinizing the impact of physiological fatigue and gaze behavior on shooting performance in elite and sub-elite biathletes.

Design: Ten members of the German national senior team (elite) and 13 members of the German national junior team (sub-elite) participated in a performance test. They conducted a roller skiing test on a treadmill including four increasing intensity levels followed by shooting blocks of five shots in both prone and standing position.

Methods: Physiological measurements consisted of heart rate and blood lactate, shooting performance data included shooting accuracy and time. Eye movements were assessed, i.e. the duration of the final fixation, using a gun-mounted eye tracking system.

Results: Physiological fatigue systematically increased across intensity levels. There were no differences between elite and sub-elite biathletes in percentage shooting accuracy. However, elites needed shorter shooting times than sub-elites. Both groups showed increased range times with increased workload levels in prone and standing positions. Yet, there was no effect on shooting accuracy. Finally, analyses of a subset of data did not show any effect of final fixation duration on shooting accuracy.

Conclusions: Physiological fatigue seems to have no impact on shooting accuracy, but rather affects shooting times in expert biathletes. Furthermore, the duration of the final fixation does not seem to moderate shooting accuracy in elite biathletes.

3.1.1 Introduction

Biathlon is a sport that combines cross country skiing in skating technique with rifle shooting. Successful performance in biathlon demands high shooting accuracy and fast shooting times under tremendous physiological workload. According to the rules of the International Biathlon Union (2018) competitors ski a cross country course divided into various loops, and execute two or four shooting blocks in between loops. Competitions differ concerning the to-be-skied distances depending on the type of competition and gender. The shooting blocks typically alter between shooting in prone position and standing positions, always consisting of five consecutive shots per block. The targets are aligned horizontally, have a diameter of 4.5 cm in prone shooting and 11.5 cm in standing shooting and are presented at a distance of 50 meters. Depending on the type of competition, missing a target results in penalties (e.g., skiing an extra penalty loop). Obviously, biathlon poses high demands on physiological, motor (i.e., biomechanical) and psychological factors of performance.

Hence, past research in biathlon on the one hand focused on physiological factors such as oxygen uptake and blood parameters, for instance, with the aim to examine physiological characteristics of elite athletes and their relationship to biathlon performance (Rundell & Bacharach, 1995; Manfredini et al., 2009). On the other hand, biathlon research focussed on shooting performance, in particular, on the biomechanics underlying postural control and rifle stability (Sattlecker et al., 2014; Baca & Kornfeind, 2012; Sattlecker et al., 2017). Together this research considerably improved our understanding of the physiological and biomechanical processes determining biathlon performance. However, in keeping with the conclusions of a recent review (Laaksonen et al., 2018) there are surprisingly few studies that examined physiological and shooting parameters in conjunction. Consequently, relatively little is known about the impact of different levels of physiological workload on rifle shooting performance.

One of the first studies scrutinizing this relationship (Hoffman et al., 1992) examined how exercise at different physiological intensities affected shooting performance. Elite biathletes exercised on a cycle ergometer at different intensities and then fired five shots after each intensity level in both prone and standing positions. Shooting accuracy and shooting precision deteriorated with increasing exercise intensities for shooting in standing position, but not in prone position. Similarly, rifle stability was affected more in standing than prone shooting with increasing intensities. This study (see also Grebot et al., 2003; Ihalainen et al., 2018) showed that increasing physiological workloads can lead to decreased shooting performances in standing position.

Two recent studies question the reliability and generalizability of performance decrements under physiological workload conditions. First, Gallicchio and colleagues (2016) did not find an impact of increased physiological workload on shooting accuracy in standing position, despite applying similar methods. Gallicchio et al. were predominantly interested in the psychophysiological aspects of shooting performance and examined electroencephalographic activity (EEG). Based on specific changes in EEG patterns the authors concluded that in contrast to the behavioral data (showing no effect of workload on shooting accuracy), increased workload hindered monitoring processes generally considered to be associated with better shooting performance. A second study (Luchsinger et al., 2016) also reported no different shooting performances between conditions of rest and increased physiological workloads. Whereas biathletes outperformed cross country skiing athletes with no prior shooting experience regarding shooting accuracy, the lack of an effect of workload on shooting performance was found in both groups. Similar to Gallicchio et al. (2016), Luchsinger and colleagues (2016) aimed at examining the role of focused attention on shooting performance and therefore assessed EEG activity. In contrast to Gallicchio et al. (2016), they did not find differences in frontal theta activity between conditions. Yet, higher frontal theta activities related to better shooting performance (in skilled biathletes) and lower activities related to worse shooting performances in inexperienced cross country skiers. Luchsinger et al. (2016) concluded that focused attention tends to predict successful shooting performance, but that physiological workload does neither diminish focused attention nor shooting performance in biathlon.

The contention that focused attention may play a crucial role in successful biathlon shooting is corroborated by a study examining gaze control in biathlon shooting (Vickers & Williams, 2007). Though the main aim of their study was to scrutinize changes in visual attention and shooting performance depending on different psychological pressure situations, Vickers and Williams (2007) did so at five different physiological workload levels. Ten members of Canada's junior and senior national biathlon team performed a stepwise level test on a cycle ergometer, with power output levels set at 55%, 70%, 85% and 100% of each athlete's maximal individual oxygen uptake. In the rest condition as well as after every workload level, participants performed two blocks of five shots each in a simulated shooting task, using a laser system and targets with 10 mm diameter while shooting from a five meters' distance. Among other measures, heart rate was monitored, shooting accuracy was determined and gaze behavior collected. Regarding the latter, the authors particularly focused on the duration of the final fixation (dubbed as Quiet Eye; QE) which was assessed using an ASL 501 Eye Tracking System. In contrast to some authors (Gallicchio et al., 2016; Luchsinger et al., 2016), yet in line with others (Hoffman et al., 1992; Grebot et al., 2003; Ihalainen et al., 2018), Vickers and Williams found that with increasing exercise intensity shooting accuracy decreased. Better shooting performances were associated with longer final fixations at submaximal physiological workload levels (including 55%, 70% and 85% of athletes' maximal individual oxygen uptake). It hence seems reasonable to conclude that visual attention (e.g. Luchsinger et al., 2016), also when operationalized as gaze behavior, and in specific the duration of the final fixation (Vickers & Williams, 2007), may play a crucial role in biathlon shooting performance.

Despite converging evidence that attention and in specific visual attention seems to moderate shooting performance in biathlon (Luchsinger et al., 2016; Vickers & Williams, 2007), there is no consensus yet as to whether increasing physiological workload leads to deteriorations of performance (Hoffman et al., 1992; Grebot et al., 2003; Ihalainen et al., 2018; Vickers & Williams, 2007) or not (Gallicchio et al., 2016; Luchsinger et al., 2016). A recent systematic review (Schapschröer et al., 2016) revealed that moderate to high-intensity exercise improves perceptual-motor performance in general, speed-related tasks (not specific to the participants' domain of exercise), but not in accuracy-related tasks across a broad range of sports (including e.g. soccer, orienteering, cycling). Yet, the review also concluded that when looking at specific tasks within a given sport, findings tend to be quite heterogeneous regarding the impact of physiological workload on accuracy (ranging from no effects at all to performance improvements and deteriorations). It has to be noted that the number of studies addressing this relation in sports in general (applying both specific physical exercise and specific perceptual-cognitive tasks) is very low. The heterogeneity of the results also applies to the inconsistent findings regarding the effect of physiological workload on shooting performance in biathlon, at times showing performance deteriorations (Hoffman et al., 1992; Grebot et al., 2003; Ihalainen et al., 2018; Vickers & Williams, 2007) but also null effects (Gallicchio et al., 2016; Luchsinger et al., 2016). Finally, in biathlon, with the exception of one study (Ihalainen et al., 2018), shooting performance has typically been determined by accuracy measures, whereas shooting times have been largely neglected. However, as highlighted by Schapschröer et al. (2016) research needs to be precise and specific regarding, among other things, the choice of the multiple variables that may affect performance when aiming to uncover their contributions to performance in representative conditions. Following this recommendation and given that successful biathlon shooting demands both fast shooting times and high shooting accuracy, in the current study we included both measures.

The aims of the present study were twofold: first, based on the conflicting findings of previous research we examined the impact of physiological fatigue on shooting performance in biathlon. Second, given that Vickers and Williams (2007) is thus far the only study examining gaze behavior, the present study aimed at conceptually replicating the study in a more representative performance setting. That is, in contrast to Vickers and Williams (2007) who a) induced physiological workload using a cycle ergometer, b) applied a simulated shooting task without ammunition, c) had participants shooting on a single instead of five horizontally aligned targets, d) did not use the official biathlon shooting distance, e) focused exclusively on standing shooting and f) did not assess shooting time but focused merely on shooting accuracy, here we applied a biathlon specific protocol which closely resembles the conditions faced in a real biathlon competition. In keeping with recent research on representative designs (Dicks et al., 2010) we predicted stronger effects of final fixation durations on shooting performance, if the effects found in the original study (Vickers & Williams, 2007) proved to be valid and generalizable to a representative task design. However, if the reported effects from the less representative task cannot be replicated, then this may question the robustness and/ or the generalizability of the originally reported effects from lab to real competition situations in expert biathletes.

To examine the impact of physiological workload on shooting performance in biathlon experts and to test our hypotheses regarding the role of gaze behavior, elite and sub-elite biathletes participated in a stepwise roller skiing treadmill test. This test included increasing workload levels and shooting blocks of five shots alternating in prone and standing position. Physiological parameters were measured as heart rate and blood lactate. Shooting accuracy, shooting times, radial errors and aiming trace speed were measured as dependent variables of shooting performance. Fixation durations of the final fixations were captured using a self-developed gun-mounted eye tracking apparatus.

3.1.2 Methods

Ten members of the German national senior team (mean age: 23.40 ± 2.68 years, four females) and 13 members of the German national junior team (mean age: 19.54 ± 0.88 years, five females) participated in the study. The German national senior team members regularly participate at World Cups, World Championships, Olympics and International Biathlon Union (IBU)-Cup and are referred to as elite group. The German national junior team members regularly participate at Junior World Championships, Junior IBU-Cup and European Championships and are referred to as sub-elite biathletes. The study protocol was approved by the Ethical Committee of the Faculty of Social and Behavioral Sciences of the Friedrich Schiller University Jena. All participants gave written informed consent before testing.

The performance test was conducted on a roller skiing treadmill (POMA Maschinen- und Anlagenbau GmbH, Porschendorf, Germany & Wige Data GmbH, Leipzig, Germany). All athletes were using the same roller skis (Marwe Oy, Hyvinkää, Finland) and skiing poles adjusted to their individual length (Swix, Lillehammer, Norway).

The biathletes were shooting on a 50 meters indoor shooting range located 20 meters from the treadmill. The biathletes were shooting at original biathlon targets (4.5 cm diameter prone shooting; 11.5 cm diameter standing shooting) with real ammunition, using their individual biathlon rifle (min. weight 3.5 kg).

Physiological data was collected using a Polar (Polar Electro Oy, Kempele, Finnland) heart rate belt (RS 800 CX, H3). The data was transferred to the *Polar Pro Trainer* software. Blood lactate was analyzed using standard protocols (BIOSEN C-Line, EKF Diagnostik, Barleben, Germany) after taking 20 µl capillary blood from the athlete's earlobe.

A Scatt (SCATT Eletronics LLC, Moscow, Russia) shooting system (MX - 02) provided detailed information about the shooting performance such as radial error from the target's center and aiming trace (including aiming trace speed) before the shot. The system consists of a wired optical unit (weight: 30 g) attached to the gun barrel which is connected to a PC, using the software *Scatt Expert*.

A pilot-test revealed that standard and remote mobile eye trackers are unsuitable for experiments in biathlon shooting due to spatial constraints when using the rifle, precision of eye trackers and inconvenience of wearing the eye tracker.

We consequently developed an eye tracker tailored to the special requirements of biathlon shooting, see Hansen et al. (2019)1. For a detailed description of technical information and how limitations of existing eye trackers were solved, please consult the online supplementary material (https://doi.org/10.1016/j.jsams.2020.02.010).

The tests were conducted at the national team's training site. The athletes were familiar with the performance test as part of their regular preparation for the winter season. They were informed that the regular test protocol was extended by gathering gaze tracking data using the developed eye tracking system. On arrival, first blood lactate was taken under rest conditions and the athletes were fitted with a Polar heart rate monitor. Then the Scatt system and the eye tracking system were mounted on the participants' gun barrel. After calibration of the Scatt System the athletes

[1] Hansen et al. (2019) is a proceedings paper presented at the Symposium on Eye Tracking Research and Applications (ETRA '19) in Denver. It predominantly served the description of the specifics of the gun-mounted eye tracking apparatus. For validation purposes it also included a subset (nine sub-elite biathletes) of data presented in this paper.

were free to fire a number of warm-up shots in both prone and standing position. Subsequently, they absolved a warm-up of six minutes at the roller skiing treadmill. Afterwards the performance test on the treadmill started.

A standardized performance test protocol for female and male senior biathletes (elite) and an adapted test for female and male junior athletes (sub-elite) was conducted. The test consisted of six intensity levels. Each level contained the same sequence of inclines in the range of zero to seven degrees (i.e., 1, 3, 6/7, 0/1 degrees). The treadmill's speed differed between the junior and senior biathletes' test as well as between females and males at every level. Each level lasted six minutes for male athletes and six minutes and 30 seconds for female athletes. Immediately after finishing each level, the athlete roller-skied to the firing line of the indoor shooting range (which took approximately 15 seconds). The athletes loaded the gun that was placed at the shooting range and fired a sequence of five shots. Following the shooting the participants returned to the treadmill where blood was taken for lactate analyses and the next level on the roller skiing treadmill started. This procedure was repeated four times: in line with the standardized test protocol the female participants were shooting after the first, second, third and fourth level and the male participants were shooting after the second, third, fourth and fifth level. The lactate level analysis (see results: Physiology) confirmed that the adopted test led to highly similar physiological fatigue levels between groups. Every athlete performed prone and standing shooting in an alternating order always starting with prone position. The total time of testing for each participant took about 1.5 hours.

Physiological data and shooting performance data were first digitized. Then the eye tracking data was coded using an annotation tool developed for this purpose (see Hansen et al., 2019 and supplementary material). Based on frame-by-frame analyses, the finger's final movement, blinks, shoot recoils and eye movements were identified and manually annotated. The onset of the final fixation was identified by backtracking frame by frame from the identified shot. The duration of final fixation was calculated from the onset to the shot. To analyze final fixation duration independent of shooting time, the relative final fixation duration was calculated for every shooting block as the quotient of mean duration of final fixation and sequence duration. We defined the shooting sequence duration as starting with the moment when the chin touched the rifle for the first time before the first shot and ending when the chin was leaving the rifle after the athlete had fired the block of five shots (for more detailed information, see Hansen et al., 2019).

First, as a manipulation check we tested whether increasing workload levels led to increased physiological fatigue and tested for the comparability between elite and sub-elite test protocols. Blood lactate and heart rate were analyzed using a 2 (group: Elite, Sub-elite) x 4 (workload level: 1, 2, 3, 4) analysis of variance (ANOVA) with repeated measures on the last factor. Heart rate was analyzed as percentage of maximal heart rate to control for individual differences. Second, to asses shooting performance, both shooting time and shooting accuracy were analyzed separately. For shooting time, the two dependent variables range time and sequence time were analyzed using a 2 (group: Elite, Sub-Elite) x 2 (workload level 1,2) x 2 (position: prone, standing) ANOVA with repeated measures on the last two factors. Due to technical issues the analysis of sequence time included a subset of data (7 elite & 6 sub-elite). Likewise, the dependent variables related to shooting accuracy (radial error, aiming trace speed) were analyzed by using 2 (group: Elite, Sub-Elite) x 2 (workload level 1,2) x 2 (position: prone, standing) ANOVA with repeated measures on the last two factors. Also due to technical issues, the analysis of radial error included 4 elite and 12 sub-elite, and the analysis of aiming trace speed included 4 elite and 10 sub-elite. A Wilcoxon signed-ranked test was used to compare shooting accuracy across the two increasing workload levels in prone shooting and standing shooting separately as the assumption of normal distribution was violated for 'percentage accuracy'. The data for this analysis was split by the factor group to be able to compare elite with sub-elite biathletes. Third, gaze data was analyzed using a 2 (group: Elite, Sub-Elite) x 2 (workload level 1,2) x 2 (position: prone, standing) ANOVA with repeated measures on the last two factors for both total duration of final fixation and relative duration of final fixation. Finally, the correlation between mean duration of total final fixation and percentage accuracy was analyzed using Kendall rank correlation coefficients (Kendall's tau) as a non-parametric test appropriate for small sample sizes (Bonett & Wright, 2000). Again, due to technical issues the analysis of total duration of final fixation included 7 elite and 6 sub-elite while the analysis of relative duration of final fixation included 6 elite and 6 sub-elite athletes.

Bonferroni-corrected pairwise comparisons were used as post-hoc tests. Greenhouse-Geisser corrections were applied, in case the sphericity assumption (Mauchly's test) was violated. Effect sizes were calculated as η_p^2: values of .01, .06 and .14 were taken to reflect small, medium and large effects, respectively (Cohen, 1988). In addition, Cohen's d is reported as measure of effect size for pairwise comparisons and for Wilcoxon signed-ranked tests: values of 0.2, 0.5 and 0.8 indicate small, medium and large effects (Cohen, 1988). We applied a significance level of 0.05 for all statistical tests.

3.1.3 Results

The 2 x 4 ANOVA for blood lactate revealed a significant main effect for workload level, $F(1.10, 23.4) = 89.035$, $p < .001$, $\eta_p^2 = .809$. Pairwise comparisons indicated significant differences of mean blood lactate between every workload level with medium effect sizes, *ps* < .001, *Cohen's d* (WL 1 vs. WL 2) = .658, *Cohen's d* (WL 2 vs. WL 3) = .649, *Cohen's d* (WL 3 vs. WL 4) = .631. Mean lactate (elite and sub-elite) was increasing from 2.39 mmol/l (SD = .90 mmol/l) at the end of the first workload level (WL) to 3.13 mmol/l (SD = 1.33 mmol/l) at WL 2, 4.21 mmol/l (SD = 1.94 mmol/l) at WL 3 up to 5.55 mmol/l (SD = 2.30 mmol/l) at WL 4. There was no significant main effect for group ($F(1,21) = .036$, $p = .850$, $\eta_p^2 = .002$) and also no significant interaction workload level by group ($F(1.10, 23.4) = .026$, $p = .908$, $\eta_p^2 = .001$). Similar to lactate level, the 2 x 4 ANOVA for heart rate (percentage of maximal heart rate) revealed a significant main effect for workload level, $F(1.27, 26.6) = 235.152$, $p < .001$, $\eta_p^2 = .918$. Follow-up pairwise comparisons indicated significant differences of mean heart rate between every workload level with large effect sizes, *ps* < .001, *Cohen's d* (WL 1 vs. WL 2) = 1.000, *Cohen's d* (WL 2 vs. WL 3) = 1.059, *Cohen's d* (WL 3 vs. WL 4) = .983. In absolute values, mean heart rate was increasing from 171.1 bpm (SD = 10.5 bpm) at WL 1, to 177.2 bpm (SD = 9.9 bpm) at WL 2, to 182.6 bpm (SD = 9.2 bpm) at WL 3, and to 186.4 bpm (SD = 8.3 bpm) at WL 4. There was neither a significant main effect for group ($F(1,21) = 1.215$; p = .283, $\eta_p^2 = .055$) nor a significant interaction between workload level and group ($F(1.27, 26.6) = .304$, $p = .640$, $\eta_p^2 = .014$).

The 2 x 2 x 2 ANOVA on range time revealed a significant main effect for workload level, $F(1,21) = 5.928$, $p = .024$, $\eta_p^2 = .220$, indicating longer shooting times at increased workload levels. The main effect for position was also significant, $F(1,21) = 8.939$, $p = .007$, $\eta_p^2 = .299$, indicating longer shooting times in prone position than in standing position. As illustrated in Figure 9, there was also a significant main effect for group, $F(1,21) = 13.360$, $p = .001$, $\eta_p^2 = .389$, indicating longer shooting time for sub-elite biathletes compared to elite biathletes. There were no significant two-way or three-way interactions (all $Fs(1,21) < .17$, all $ps \geq .68$, all $\eta_p^2 \leq .008$).

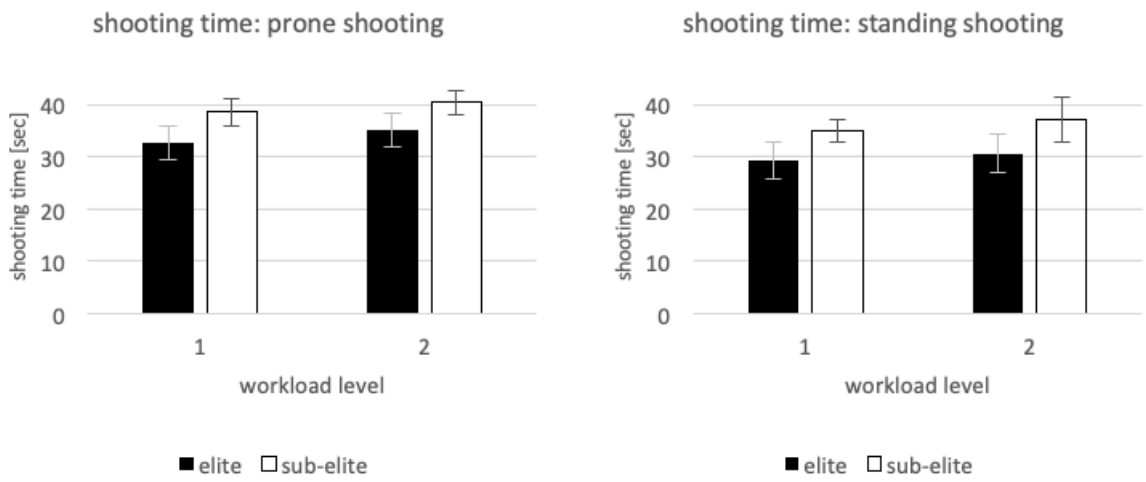

Figure 9. Mean shooting time for the shooting series in prone shooting and in standing shooting under increasing workload conditions. Error bars are representing the 95% confidence interval.

The 2 x 2 x 2 ANOVA on the duration of shooting sequence (7 elite & 6 sub-elite) revealed neither significant main effects for workload level ($F(1,11) = .087$, $p = .773$, $\eta_p^2 = .008$) nor for position ($F(1,11) = 3.159$, $p = .103$, $\eta_p^2 = .223$) or group ($F(1,11) = 4.704$, $p = .053$, $\eta_p^2 = .300$). There were also no significant two-way or three-way interactions (all $Fs(1,11) \leq 1.71$, all $ps \geq .687$, all $\eta_p^2 \leq .015$).

The analysis of percentage accuracy (Wilcoxon signed-ranked test) revealed neither for elite nor for sub-elite biathletes differences between workload level 1 (*Mdn* Elite: 80; *Mdn* Sub-Elite: 80) compared to the increased workload level 2 (*Mdn* Elite: 80; *Mdn* Sub-Elite: 80) in prone shooting; effect sizes indicate small effects (Elite: $T = 6$, $p = .655$, *Cohen's d* = .286; Sub-Elite: $T = 22$, $p = .565$, *Cohen's d* = .324). Also for standing shooting no differences between workload level 1 (*Mdn* elite: 80; *Mdn* sub-elite: 80) and WL 2 (*Mdn* elite: 100; *Mdn* sub-elite: 80) were found (elite: $T = 10.5$,

p = .550, *Cohen's d* = .385; sub-elite: T = 22, p = .565, *Cohen's d* = .324). Non-parametric tests are reported as the percentage accuracy data was not normally distributed as outlined in the data analysis section. However, given that these tests do not allow to analyze potential interactions, we also ran the corresponding 2 (group: Elite, Sub-Elite) x 2 (workload level: 1, 2) x 2 (position: prone, standing) ANOVA with repeated measures on the last two factors. This ANOVA did neither show significant main effects nor interactions.

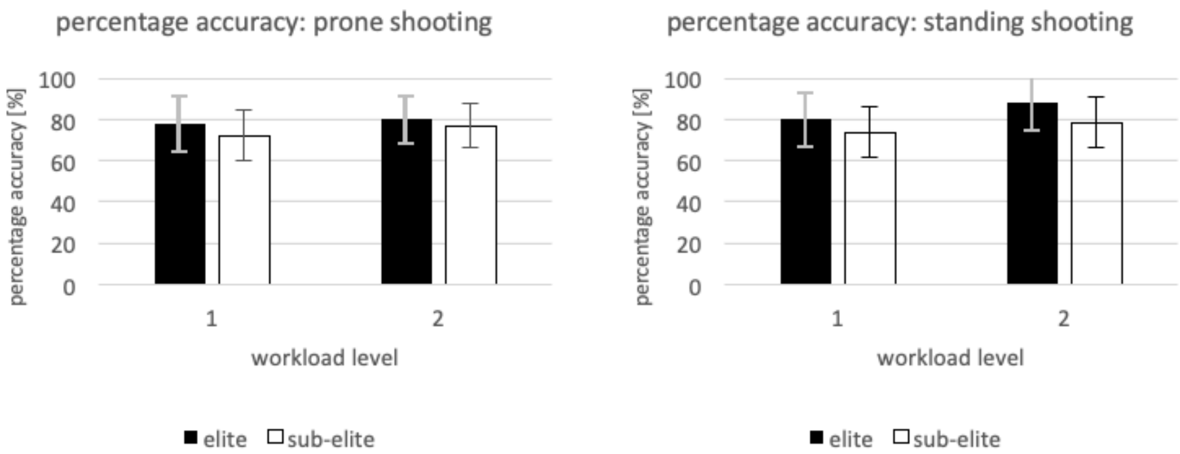

Figure 10. Percentage accuracy in prone shooting and standing shooting across workload levels. Error bars are representing the 95% confidence interval.

The 2 x 2 x 2 ANOVA to analyze radial error (4 elite & 12 sub-elite) revealed a significant main effect for position, $F(1,14) = 33.102$, $p < .001$, $\eta_p^2 = .703$, indicating a larger radial error for standing shooting compared to prone shooting. Neither a significant main effect for workload level, ($F(1,14) = 1.705$, $p = .213$, $\eta_p^2 = .109$) nor for group, ($F(1,14) = 1.035$, $p = .326$, $\eta_p^2 = .069$) and no significant two-way (all $Fs(1,14) \leq 3.32$, all $ps \geq .090$, all $\eta_p^2 \leq .191$) or three-way interaction ($F(1,14) = .250$, $p = .625$, $\eta_p^2 = .018$) was observed.

The 2 x 2 x 2 ANOVA to analyze aiming trace (4 elite & 10 sub-elite) revealed a significant main effect for position indicating that the aiming trace speed was lower in prone shooting than in standing shooting, $F(1,12) = 9.842$, $p = .009$, $\eta_p^2 = .451$. No significant effects were found for workload level ($F(1,12) = 2.213$, $p = .163$, $\eta_p^2 = .156$) or for group ($F(1,12) = 2.901$, $p = .114$, $\eta_p^2 = .195$). The analysis revealed no significant interactions (all $Fs(1,12) \leq 3.39$, all $ps \geq .090$, all $\eta_p^2 \leq .220$).

The 2 x 2 x 2 ANOVA to determine total duration of final fixation (7 elite & 6 sub-elite) revealed a significant main effect for position, $F(1,11) = 10.334$, $p = .008$, $\eta_p^2 = .484$, indicating shorter final fixation times in standing shooting than in prone shooting. There were neither main effects for workload level ($F(1,11) = .117$, $p = .739$, $\eta_p^2 = .011$) nor group ($F(1,11) = 1.034$, $p = .331$, $\eta_p^2 = .086$), and no interaction effects (all $Fs\ (1,11) \leq .387$, all $ps \geq .547$, all $\eta_p^2 \leq .034$). Mean durations of final fixation in prone shooting ranged between 2490.56 ms (SD = 832.33 ms; first prone shooting) and 2578.89 ms (SD = 647.14 ms; second prone shooting) while fixation duration in standing shooting ranged between 2270.98 (SD = 611.45 ms; first standing shooting) and 2257.06 (SD = 691.35 ms; second standing shooting). ANOVA on the relative final fixation duration (6 elite & 6 sub-elite) revealed no significant main effects for workload level ($F(1,10) = .765$, $p = .402$, $\eta_p^2 = .071$), position ($F(1,10) = 1.284$, $p = .284$, $\eta_p^2 = .114$), or group ($F(1,10) = .004$, $p = .949$, $\eta_p^2 = .000$). No interaction effects were found (all $Fs(1,10) \leq .296$, all $ps \geq .598$, all $\eta_p^2 \leq .029$).

In line with the visual neuroscience literature, a fixation is often defined as a period between two saccadic eye movements in the absence of a smooth pursuit (Holmqvist et al., 2011) around 100ms or longer (Rayner, 1998). In biathlon it is important to maintain high head and rifle stability, and therefore in the present study we included an additional criterion for the definition of fixation, that is, head stability. Following Steinmann, Cushman and Martins (1982), head movements influence eye stability during a fixation but can also be seen as part of it, so we additionally analyzed gaze behavior without the criterion of head stability. Findings were similar, showing a significant effect of position for total duration of final fixation ($F(1,11) = 8.62$, $p = .014$, $\eta_p^2 = .439$), but no effects of workload level or group. No interactions were found. A subsequent analysis of the relative final fixation duration showed neither significant main effects nor interactions.

As illustrated in Figure 11, biathletes showed large individual differences in the duration of final fixation even at 100% accuracy level, ranging from approximately 950ms to approximately 4000ms. Finally, there were no significant relationships between mean duration of total final fixation and percentage accuracy, calculated for every workload level (WL1: $\tau_1 = -.110$, $p_1 = .554$; WL2: $\tau_2 = -.150$, $p_2 = .449$; WL3: $\tau_3 = .207$, $p_3 = .334$; WL4: $\tau_4 = .143$, $p_4 = .468$).

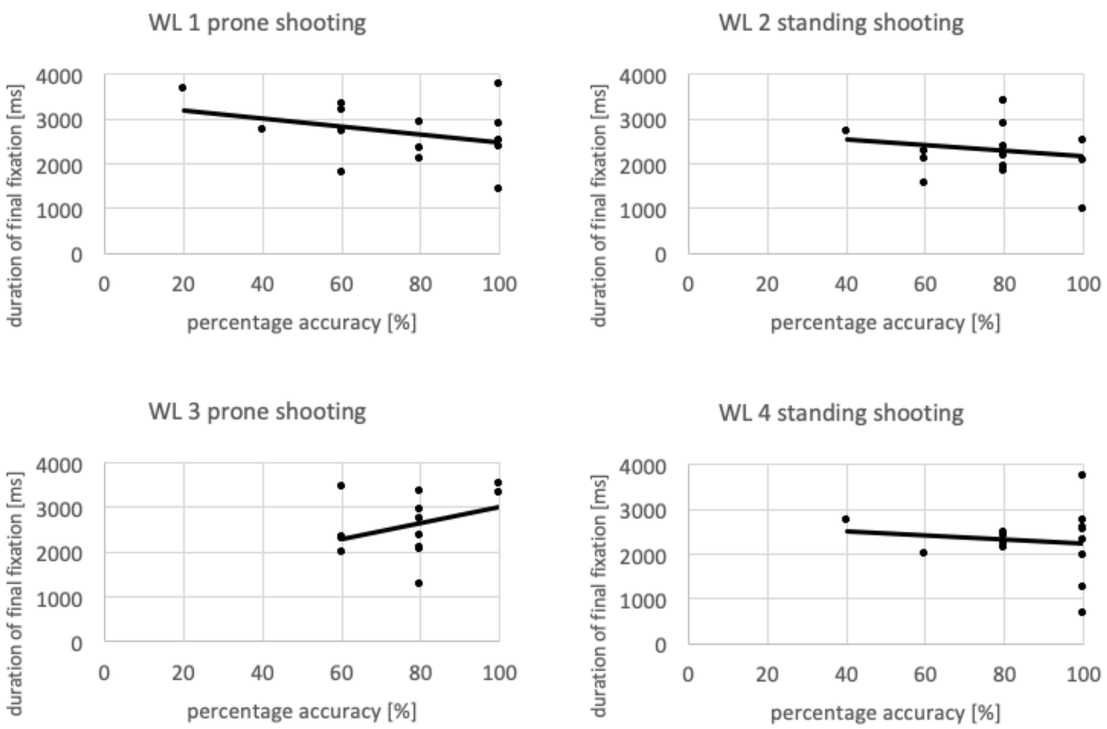

Figure 11. Scatterplot displaying the relationship between duration of final fixation and percentage accuracy in workload level 1 (prone), WL 2 (standing), WL 3 (prone) and WL 4 (standing).

3.1.4 Discussion

The aims of the present study were to examine (i) the impact of physiological workload on shooting performance in biathlon experts and (ii) the role of gaze behavior therein. Regarding the first aim, our results showed, first, that shooting time (in specific: range time) increased with increasing workload levels in both elite and sub-elite biathletes with relatively large effect sizes. Yet, there was no effect on percentage accuracy. Thus far only one study examined the impact of physiological workload on shooting time (Ihalainen et al., 2018). Similar to our findings, this study also found an increase of shooting time under sub-maximal workload conditions.

Shooting range time showed large differences between elite and sub-elite biathletes, with elites showing shorter shooting times than sub-elites. This is in line with Kreivėnaitė (2012), who found shorter shooting times in seniors than in juniors competing in the World Championships 2011/2012. Shooting sequence time also indicated a large effect for group ($\eta_p^2 = .300$) with shorter times for elites compared to sub-elites (note that this effect slightly failed to attain significance, $p = .053$).

Given the small sample size for this particular analysis, certainly more research is necessary to examine whether this effect remains robust with larger sample sizes. Taken together, shooting time in general seems to differentiate between elite and sub-elite biathletes.

In contrast, elite and sub-elites did not differ in percentage accuracy or radial error. Taking into account that radial error analysis included (only) 4 elite versus 12 sub-elite biathletes and that the results showed a medium effect size ($\eta_p^2 = .069$), again we cannot rule out that if sample size was increased the effect may become significant. The same is true for aiming trace speed ($\eta_p^2 = .195$). In contrast to shooting times, increasing physiological fatigue did not affect percentage accuracy. While these findings are in line with Luchsinger et al. (2016) and Gallicchio et al. (2016), they are in conflict with several other studies reporting a deterioration of shooting accuracy with increasing fatigue (Hoffman et al., 1992; Grebot et al., 2003; Ihalainen et al., 2018; Vickers & Williams, 2007). Given the small sample sizes (and hence lack of statistical power) in both previous and our work, we take our results to question the evidence for a large effect of physiological fatigue on shooting accuracy in biathlon and call for more (better powered) research.

Next to these inconsistent findings, there is also a large heterogeneity concerning the applied methodological approaches with respect to physiological workload (e.g., cycling ergometer (Hoffman et al., 1992; Vickers & Williams, 2007; Gallicchio et al., 2016) versus roller skiing (Ihalainen et al., 2018; Luchsinger et al., 2016). Given these methodological differences and the small number of studies addressing the interaction of skiing and shooting, we further advice the use of more consistent methodological approaches (regarding workload protocols) across labs in an attempt to provide evidence that will stand the test of time.

Studies also differ concerning the assessment and ecological validity of shooting accuracy. With the exception of Hoffman et al. (1992), previous work examined the impact of physiological workload exclusively on shooting performance in standing position, neglecting prone shooting. Additionally, many studies used a simulated shooting task at a scaled biathlon target instead of the original shooting distance at original targets (Vickers & Williams, 2007; Ihalainen et al., 2018; Luchsinger et al., 2016). Real shooting differs significantly from simulated shooting regarding two main aspects: first, shooting with ammunition causes a recoil which likely affects the motor system (i.e., less stability). Importantly, because biathletes stabilize the motor system to ensure fast and accurate shooting, actual shooting may affect attentional processes differently, thereby perhaps resulting in changes to gaze behavior. Second, shooting with ammunition is resulting in an extremely loud sound (bang) which may result in an auditory distraction of (visual) attention from the target. Finally, the few studies in which participants performed real shooting were not representative for the shooting patterns in biathlon, as they only shot five times at a single, centrally presented target (Hoffman et al., 1992; Gallicchio et al., 2016). In actual biathlon competitions, the five shots are fired at five horizontally aligned targets and athletes have to laterally move the rifle from left to right (or vice versa) to the next target after each shot which may also impact performance in yet unknown ways.

In conclusion, the studies examining the impact of physiological workload on shooting performance in biathlon differed substantially regarding ecological validity of their study design. With the aim of providing an ecologically valid setting, the present study used a roller skiing treadmill to induce physiological fatigue. In addition, the duration was based on loop times in biathlon competitions. Similar to a biathlon race, the athletes alternatingly shot in prone and standing shooting. Using their own rifle and shooting with real ammunition at original biathlon targets allowed an assessment of shooting performance under representative conditions. Given that successful biathlon shooting demands both fast shooting times (dependent on the type of competition: correlation coefficients range between .25 and .52 for the relationship between the final result and shooting time: Cholewa et al., 2005) and high shooting accuracy throughout the entire competition, in contrast to a large number of previous studies, we considered both shooting time and shooting accuracy. Similar to physiological workload, also position (standing vs. prone shooting) affected range time, but not shooting accuracy. Range time indicated longer durations of shooting in prone compared to standing position with a large effect size ($\eta_p^2 = .299$). The differences between shooting time in prone and standing position are likely to be due to the fact that positioning for prone shooting obviously takes more time than for standing shooting (which is also in line with competition data for prone vs. standing regarding shooting times). Finally, radial errors were larger in standing shooting compared to prone shooting. Likewise aiming trace speed was higher in standing shooting which is in line with previous work (Hoffman et al., 1992; Sattlecker et al., 2017).

Concerning the examination of the gaze data, results revealed that the total duration of final fixation did not change with increasing workload levels in both elite and sub-elite biathletes. However, effect sizes indicated a medium effect for workload level on relative duration of final fixation. In addition, no correlation between duration of final fixation and shooting accuracy was found. These results are in conflict with earlier findings by Vickers and Williams (2007) who reported a significant effect of increasing workload on final fixation, but did not report effect sizes for this specific case. They reported a significant relationship between final fixation durations and shooting accuracy (with a medium effect size, i.e., the longer, the better). A number of methodological differences may account for the divergent findings: First, the participants of the present study were characterized by a higher expertise level. While athletes of the current study showed percentage accuracy between 72% (SD = 22.4%) and 88% (SD = 21.5%), participants of the previous study (Vickers & Williams, 2007) ranged between 42% (SD = 30.5%) and 74.0% (SD = 21.2%). Second, participants in the previous study performed a simulated shooting task, not real shooting. Third, the eye tracking system used in the present study was developed specifically for biathlon and minimized intrusion. It included a trigger sensor to identify the exact moment of the initial movement of the trigger finger that is firing the shot. This is critical because Vickers and Williams (2007) defined the QE as "[…] the final fixation that was maintained on any part of the target for more than 100ms before and after the trigger pull", and hence the exact identification of the trigger pull is crucial for data analysis. In contrast to Vickers and Williams (2007) who recorded the movement of the finger using an external camera, we used force sensors to exactly identify trigger forces and shot initiation. Given these differences, we argue that the present study might be interpreted as more representative for biathlon. And given the small sample sizes in both theirs (Vickers & Williams, 2007) and our work, the conflicting findings may be taken to question the robustness and/ or the generalizability of the originally reported effects from lab to real competition situations in expert biathletes.

Furthermore, we observed large individual differences regarding the final fixation durations with accurate shooting performance being maintained. As illustrated in Figure 11, even at 100% accuracy levels final fixation durations differed considerably between approximately 950ms and 4000ms. It seems justified to argue that (individually) different fixation behaviors may be related to successful shooting behavior.

Lastly, we found shorter final fixations in standing shooting when compared to prone shooting with a large effect (η_p^2 = .484). Because previous work exclusively focused on standing shooting, this latter finding certainly makes a novel contribution to the field. It should be noted though that these differences between prone and standing shooting are no longer significant when computing relative final fixation, indicating that the duration of final fixation correlates with the time duration of the shooting block.

In closing, we like to address a final limitation that is an inherent issue in expertise research, namely sample size. That is, expertise research is per definition dedicated to small sample sizes (McAbee, 2018) and hence often lacks statistical power when analyzed with common inferential statistics procedures. This also applies to the current study, and is the main reason for why we interpreted our data very cautiously (in particular, when due to technical issues for some dependent measures only subsets of data could be analyzed). As outlined by Schapschröer and colleagues (2016), one way to address this problem is to run replication studies and accumulate data across multiple labs, and this is certainly a view we share, followed ourselves in this study and advice for future research.

Practical Implications

- Shooting times increase with increased physiological workload while shooting accuracy is maintained. To improve biathlon shooting performance athletes and coaches should focus on maintaining short shooting times with higher workloads.
- Shooting times also discriminate elite biathletes from sub-elite biathletes and should be considered more strongly in the practical work of junior athletes and coaches in biathlon.

- Our results do not confirm that longer fixation durations are associated with better shooting accuracy in biathlon. As 100% shooting accuracy is associated with a high range of final fixation durations (approx. 950ms – 4000ms), different individual fixation strategies may lead to successful shooting performance in biathlon.

4 Building Biosocial Bridges

Having addressed the first aim of the present thesis by building a biopsychological bridge in Chapter 3.1, this section focuses on the second aim by examining social factors of biathlon performance. By doing so, I strive to fill the dashed line of the biopsychosocial framework proposed in Chapter 1.3 (see Figure 1) that is representing the lack of research in social aspects and again build the bridge to biological factors. Consequently, Chapter 4.1 investigates the effect an audience (i.e., presence vs. absence) might have on both shooting and skiing performance in expert biathletes. In the following, Chapter 4.2 focuses on the role of social context in head-to-head competitions by examining the impact of co-acting competitors on biathlon shooting performance. Both studies correspond to step 1 and step 2 suggested in Chapter 1.3 by looking at different factors in conjunction and integrating social context, while the study presented in Chapter 4.2 additionally addresses step 3 by taking a big data approach.

4.1 Selection Bias in Social Facilitation Theory? Audience Effects on Elite Biathletes' Performance are Gender-Specific.

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Abstract

Social facilitation proves robust in *conditioning tasks* (e.g., running), yet in *coordination tasks* (e.g., rifle-shooting) some studies report performance deterioration. Recent Biathlon World Cup data offered the unique opportunity to test this task-specificity (conditioning = cross country skiing, coordination = rifle-shooting). Audience restrictions due to COVID-19 allowed to compare athletes' performance in the absence (2020) and presence (season 2018/2019) of an audience. Gender-specific regulations (e.g., course length) necessitated the inclusion of gender as additional factor. Results of 83 (sprint competition) and 34 (mass start competition) biathletes revealed that task-specific social facilitation is moderated by gender: In the presence of an audience male biathletes showed performance improvements in the conditioning task and performance deteriorations in the coordination task; female biathletes showed the reverse pattern. This gender dependency may have gone unnoticed in the past due to sample selection bias (< 1/3 female), thereby questioning the generalizability of social facilitation theory.

4.1.1 Introduction

One of the most established, long-standing theories in the field of social psychology is the theory of *social facilitation* (Allport, 1924; Zajonc, 1965), positing that the presence of others influences – and typically improves – physical and cognitive performance. The very first study documenting this effect – often regarded as sport psychology's founding experiment (Aiello & Douthitt, 2001; Weinberg & Gould, 2014) – was carried out by Triplett (1898). In his seminal study, the presence of other co-acting individuals yielded increased performance in cycling competitions (which Triplett ascribed to the arousal of individuals' competitive instincts), thereby providing first evidence for the effect of others on physical performance.

While early research focused particularly on co-acting situations, subsequent studies documented effects of the mere presence of others, of passive observers, or of an audience (see Martens, 1969; Cottrell et al., 1968; Haas & Roberts, 1975). However, the direction of the effect was heterogeneous, that is both positive (e.g., Singer, 1965; Cottrell et al., 1968) as well as negative (e.g., Paulus & Cornelius, 1974; Butki, 1994) effects on performance were observed. In the following years, a plethora of theories and mechanisms aiming to explain these findings have been proposed.

Theoretical Approaches to Social Facilitation

According to Strauss (2002) theories of social facilitation can be classified in two main categories, namely activation theories and attention theories:

Activation theories claim that the presence of others yields changes in activation or arousal. For instance, the *generalized drive hypothesis* (Zajonc, 1965) postulates that increased activation facilitates dominant responses. Consequently, effects of others are moderated by task type or skill level: In simple or well-learned tasks the presence of others enhances performance (i.e., because the dominant response is correct). In complex or not well learned tasks on the other hand, the presence of others may hamper performance (i.e., dominant response is wrong). Similar arguments conceptualizing situations as challenges vs. threats have been made by Blascovich et al. (1999). Other theories highlight that it is not the mere presence of others that drives increases in activation, but rather the prospect of one's performance being evaluated (see Henchy & Glass, 1968; Cottrell et al., 1968; for such evaluation approaches). Finally, the *monitoring model* suggests that the crucial element driving arousal is instead the situation's uncertainty (i.e., novel situation, unknown spectators; Guerin, 1983).

Attention theories, on the other hand, propose that the presence of others predominantly affects individuals' attention. For example, Baron's (1986) *overload hypothesis* traces performance decrements in complex tasks back to attentional exhaustion. Enhancements in simple tasks are thought to be caused by focusing exclusively on relevant stimuli. In contrast, Carver and Scheier's (1981) *feedback-loop model* suggests that being observed by others increases self-awareness which in turn renders discrepancies between actual and ideal behavior more salient (thus strengthening a continuous feedback loop).

Finally, theories such as Sanders et al.'s (1978) *distraction-conflict hypothesis* incorporate both changes in arousal and attention in order to explain social facilitation effects.

Social Facilitation is Dependent on Task Type

It is noteworthy that a number of these theories explicitly acknowledge the impact of task complexity or task type on social facilitation effects: In general, performance is thought to increase in simple or well-learned tasks, but thought to decrease in complex or unfamiliar tasks. Depending on the respective theory, the moderating role of task complexity is explained by different processes such as changes in activation or attention (see above). This notion is supported by Bond and Titus' (1983) meta-analysis assessing the role of task complexity in a total of 241 studies. Additionally, they also differentiated between so called quantitative (e.g., speed) and qualitative (e.g., accuracy) measures of performance and found performance benefits in simple, quantitative tasks (Cohen's d = .32) and performance decrements in complex, qualitative tasks (Cohen's d = -.36).

Strauss (2002) adopted a similar classification in extending these findings to the realm of motor tasks. Specifically, the presence of others tends to improve performance in so called *conditioning tasks* relying predominantly on stamina or muscle strength such as cycling, running, or weight lifting. These tasks tend to be simple, generally require little or no learning and are mostly determined by the organism's energy (Strauss, 2002). Strauss (2002) related social facilitation in conditioning tasks to, for instance, activation theories (e.g., *generalized drive hypothesis* by Zajonc, 1965), assuming that changes in activation through the presence of others are beneficial to performance in tasks of low complexity as it facilitates dominant responses that are correct in simple tasks but might be the wrong ones in complex tasks. Similarly, attention theories such as the *overload hypothesis* (Baron, 1986) predict performance enhancements in simple tasks caused by an exclusive focus on relevant stimuli.

For instance, Worringham and Messick (1983) conducted an ingenious real-world study of runners' performance under various forms of social influence by unobtrusively measuring runners' speed along a popular running path. Next to the path a woman was sitting either facing away from the runners (mere presence condition) or facing the runners instead (evaluation condition). In a third control condition, the woman was absent. Only in the evaluation condition significant accelerations in running speed were observed. Similar findings are reported by Rhea et al. (2003), who documented increased one-repetition maximum bench press performance in the presence of an audience (compared to co-action).

So called *coordination tasks* on the other hand depend predominantly on motor coordination as required in precision or balance tasks. They involve the synchronization of various body systems and generally require a learning phase (Strauss, 2002). In contrast to conditioning tasks, social facilitation theories assume performance decrements in complex coordination tasks traced back to, for instance, attentional exhaustion (Baron, 1986), interfering dominant responses (Zajonc, 1965), or threat rather than challenge (Blascovich et al., 1999). However, while conditioning tasks are generally seen to be simple, coordination tasks can represent both simple and complex tasks (Strauss, 2002) - a fact that may account for the equivocal empirical findings of social facilitation in this task type (Strauss, 2002) that generally come from laboratory studies. For example, performance decrements (in the presence of others) are reported in the learning phase of a novel task (e.g., goal pursuit task in Martens, 1969; mirror tracing in Haas & Roberts, 1975; pursuit rotor task in Butki, 1994), whereas performance benefits are reported for performance of well learned tasks (e.g., Martens, 1969; Haas & Roberts, 1975) or in more skilled participants (e.g., balance task in Singer, 1965).

A similar picture emerges for studies assessing actual sports performance (vs. laboratory tasks) – also because performance in many sports is determined by a combination of conditioning and coordination tasks (e.g., soccer, tennis, gymnastics). For example, focusing on tennis matches Dube and Tatz (1991) showed that the presence of others yields performance enhancements for skilled pupils but performance decrements for less-skilled pupils. Similar negative effects of others' presence were found for unskilled karate students aiming to hit a target as accurate and often as possible (Bell & Yee, 1989). By contrast, several other studies failed to find any effects (e.g., squash performance in Forgas et al., 1980) or even found performance decrements in high skilled participants (e.g., gymnastics: Paulus & Cornelius, 1974).

To summarize, evidence to date largely supports social facilitation effects in conditioning tasks. In contrast, evidence for social facilitation in coordination tasks is less clear cut, with some studies reporting positive and others negative effects (also depending on participants' skill level) or even no effects. Additionally, only few studies utilized ecologically valid, real-world conditions (i.e., outside the laboratory). On the one hand, this is not surprising because systematically manipulating the presence of, for instance, an audience during elite sport competitions is fraught with obstacles and at odds with the interests of athletes, sports marketers, and fans. On the other hand, testing theory by means of actual behavior under real world conditions would offer superior ecological validity, a forgotten virtue of social psychological research, as has been eloquently pointed out by Baumeister, Vohs, and Funder (2007). As such there is a need for research addressing both a) the effects of social facilitation on coordination tasks and b) social facilitation effects in ecologically valid settings.

Coincidentally, this year's various lockdown measures that followed in the wake of the COVID-19 pandemic represented a one-of-a-kind opportunity for implementing such a paradigm in elite sport. Specifically, we utilized official competition data provided by the International Biathlon Union (IBU) on Biathlon World Cup events that were held before empty ranks in 2020 (due to lockdown regulations) but took place with the usual audience in the previous two winter seasons at the very same locations.

In addition, biathlon offers the unique opportunity to test task-specific effects of social facilitation within individuals because a biathlete's performance is jointly determined by cross-country skiing performance (conditioning task) and rifle shooting (coordination task). Furthermore, in several countries biathlon represents one of the most popular winter sports with more than 100.000 spectators attending a World Cup event. Spectators are present both along the skiing course and at the shooting range and have thus the opportunity to react (e.g., cheer or groan) to both athletes' skiing and shooting performance, presumably increasing the pressure on the biathletes (Harb-Wu & Krumer, 2019). Most importantly though, performance on both tasks is assessed separately, allowing to dissociate task dependent social facilitation effects.[2] In combination with the lockdown induced absence (vs. presence) of an audience this allowed for a classic repeated measures 2 x 2 design with measures of elite athletes' actual behavior (i.e., skiing and shooting performance) in real World Cup competitions.

This paradigm allows to test social facilitation theory's prediction (Allport, 1924; Zajonc, 1965) that performance in a conditioning task (i.e., skiing performance) will benefit from the presence of an audience (see also Strauss, 2002). In addition, and within the same participants and competitions, we additionally tested whether performance in a coordination task (i.e., shooting performance) would either suffer (e.g., Butki, 1994) or improve (e.g., Singer, 1965; Haas & Roberts, 1975) from the presence of an audience. Consequently, we aimed at examining the moderating role of task complexity that underpins most of the presented social facilitation theories (activation and attention theories) and is qualified as type of task (i.e., conditioning vs. coordination task) in motor performance (Strauss, 2002).

As dependent measures we analyzed (i) the cross country skiing times (independent of time spent at the shooting range) and (ii) shooting performance including shooting times and shooting accuracy. Note that because competitions of male and female biathletes differ regarding course length we included gender as an additional factor into all analyses.

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[2] Previous research has employed biathlon data successfully for highlighting task dependent effects of a supportive (vs. less supportive) audience by comparing shooting and skiing performance between home and away contests (Harb-Wu & Krumer, 2019).

4.1.2 Methods

Archival Data

All analyses were based on competition data available at the International Biathlon Union (IBU) datacenter (International Biathlon Union, 2020a). These data were collected by the official time keeping company for IBU-competitions in biathlon (SIWIDATA GmbH, Merano, Italy). Permission to use the data for the current analysis was kindly granted by the IBU. We selected those World Cup events that took place without spectators in 2020 (two sprint events, one mass start event) and paired them with the corresponding events (same event format, same location) in the two previous seasons. Details on these events are provided below.

Sprint Event. Sprint races of males and females at the World Cups in Nové Město na Moravě (Czech Republic) and Kontiolahti (Finland) in march 2020 took place without any spectators due to the COVID-19 pandemic. Both were included in our analyses and compared with their respective counterparts in the preceding 2018/2019 season which took place as usual in the presence of an audience (i.e., 2019 in Nové Město na Moravě and 2018 in Kontiolahti). Including only those athletes that competed in all four sprint World Cup races resulted in a sample of N = 83 (49 males and 34 female athletes).

Sprint competitions are characterized by single (i.e., individual) starts, featuring 30 second start intervals. The to-be-skied distance spans three laps and differs between women (7.5 km) and men (10 km) which may result in different physiological conditions at the shooting range (Heinrich et al., 2020). After the first and second lap athletes complete a shooting block, requiring five shots at five horizontally aligned targets from a distance of 50 m. Missing a target adds an additional 150 m penalty lap to the athletes' course. In addition, shooting blocks differ in shooting position (first: prone, second: standing). As shooting in standing position is more difficult due to requiring increased postural control, target diameter is adjusted accordingly (prone: 4.5 cm; standing: 11.5 cm; for regulatory details see International Biathlon Union, 2019).

Mass Start Event. Competition protocols of a mass start race without an audience in Nové Město na Moravě (Czech Repuclic) in March 2020 as well as its 2019 counterpart with the usual audience were analyzed. Again, only those athletes competing in both events were included in the analyses, resulting in a sample of N = 34 athletes (18 male, 16 female).

In contrast to sprint races, in mass start events all athletes start at the same time. Consequently, the position on the skiing course (women: 12.5 km, men: 15km) always corresponds to an athlete's overall ranking. Similar to sprint competitions athletes complete a shooting block in between laps. With a race spanning five laps, athletes complete the first two shooting blocks in prone and the subsequent two blocks in standing position. Similar to sprint competitions, missed targets result in the addition of 150 m penalty laps (International Biathlon Union, 2019).

Statistical Power. Working with archival data naturally determines the possible sample size. In the current study, a) only a limited number of athletes compete on an elite level and participate in World Cup competitions and b) the special circumstances of COVID-19 restrictions created a unique setting that allowed these analyses for a subset of events. As such these constitute so called resource constraints on sample size (Lakens, 2021).

To determine whether our constrained sample size allows for sufficiently powered analyses given evidence-based a priori estimates of the size of the effect, we conducted power analyses (all analyses computed with G*Power, Faul et al., 2007; see also Brysbaert, 2019, for a discussion) based on effect sizes documented in previous research (targeting a power of 80% at a significance level of .05). Social facilitation effects for conditioning tasks have been estimated around d = .32 (see Bond & Titus, 1983, p. 273). In order to detect such directional (i.e., one-tailed) effects in a repeated measures design would require a sample of at least 62. Whereas this requirement is surpassed by the data for the sprint events (N = 83, sensitivity d > .28), power for mass start events (N = 34, sensitivity d > .44) was reduced. Given that findings on coordination tasks have been quite heterogeneous (both positive and negative effects), one might be inclined to run two-tailed testing instead. Assuming an effect of d = .3 (Bond & Titus, 1983), two-tailed testing would necessitate a sample of N = 90, which again is close to the sample for the sprint event (sensitivity d > .31), but results in reduced power for the analyses of mass start events (sensitivity d > .5) an issue we will return to in the discussion.

Data Analysis

Data Preparation. Careful screening of the archival data revealed that a subset of recorded shooting blocks contained single missing values (sprint competitions: 5.93%; mass start: 5.29%). Following up on this issue with a representative of SIWIDATA (i.e., the company responsible for IBU competition protocols) revealed that missing data is most commonly due to a) a miss going astray the target area or b) errors due to crossfire. We thus treated missing data as misses (i.e., shots not hitting the target)[3]. Subsequently, based on these data, shooting accuracy was computed as the relative frequency of hits for every shooting block.

Statistical Tests. Event types of sprint and mass start were analyzed separately as sprint events feature a bigger pool of athletes than mass start events and allowed us to analyze a larger sample size (only 30 athletes participated in all six analyzed competitions and were included in both sprint and mass start analyses). Male and female biathletes vary in both skiing and shooting performance. On the one hand, course features of males and females differ remarkably (e.g., to-be-skied distance, course profile). In addition, females show on average appr. 12% slower skiing speed (Luchsinger et al., 2018) which may subsequently result in different conditions at the shooting range (e.g. different physiological workload). On the other hand, men shoot faster compared to women (Luchsinger et al., 2018; Luchsinger et al., 2019). Based on gender-specific differences in both tasks, we included gender as a factor in all analyses. In addition, shooting position (prone vs. standing position) was included as a factor in all shooting performance analyses to account for effects of postural control and target size on shooting accuracy / time (see Luchsinger et al., 2018, for lowered shooting performance in standing vs. prone position).

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[3] To ensure that results of these analyses are not unduly influenced by this procedure, we additionally re-ran the very same analyses after excluding unregistered shots. However, the pattern of results concerning the significant main effects and interactions did not differ from the original analyses described in the results, with the only exception being a main effect of gender in the mass start analyses (indicating higher shooting accuracy for women compared to men).

We analyzed the effect of audience (present vs. absent) on biathlon performance on the following dependent measures: (i) the cross country skiing times (lap times, excluding range times and penalty times; i.e., conditioning task) and (ii) shooting performance including shooting times (time spent on shooting mat; i.e., coordination task) and shooting accuracy (relative frequency of hits per shooting bloc of five shots; i.e., coordination task).

First, we analyzed lap time (i.e. skiing performance) for both competition types separately using 2 (gender: male, female) x 2 (audience: present, absent) ANOVAs with repeated measures on the last factor. Second, shooting accuracy and shooting time in sprint and mass start races were analyzed separately using 2 (gender: male, female) x 2 (shooting position: prone, standing) x 2 (audience: present, absent) ANOVAs with repeated measures on the last two factors. Please note that we included shooting position and gender due to the performance differences outlined above and had no explicit and theory-based assumption for any interaction effects.

Normality was tested using Shapiro Wilk test and visualization of data with histograms.[4]

Effect sizes were calculated as η_p^2. For the sake of completeness and comparability, we additionally included effect size measure of Cohen's d based on F-values by applying the formula $d=t\times\sqrt{(1/N)}$ with $t=\sqrt{F}$. We applied a significance level of .05 for all statistical tests. In order to control for the family-wise error rate (i.e., an increased risk of Type-I error accumulation) based on the analysis of three dependent variables (i.e., lap time, shooting accuracy, shooting time), we ran sequential Holm-Bonferroni corrections (also referred to as Holm's sequential Bonferroni procedure; Holm, 1979).

[4] Normal distribution was violated for a subset of variables/factor combinations. As several studies demonstrate the robustness of ANOVA against violations of the normal distribution assumption (Schmider et al., 2010; Blanca et al., 2017), we felt on safe ground to run the reported analyses to examine also possible interactions. To further corroborate the robustness of the effects, we additionally either ran the analyses with reciprocal transformed, normalized data or used non-parametric Wilcoxon signed-rank test. These analyses confirmed the reported results.

4.1.3 Results

Cross Country Skiing Performance

Table 2. Results of the 2 x 2 ANOVA on lap times in sprint and mass start

	Sprint Competitions				Mass Start Competitions			
Effects	*F* (1,81)	*p*	η_p^2	d	*F* (1,32)	*p*	η_p^2	d
Audience	0.05	.82	0.00	.02	6.39	.02	0.17	0.43
Gender	1169.58	**<.01**	**0.94**	**3.75**	375.03	**<.01**	**.92**	**3.32**
Gender x Audience	266.23	**<.01**	**.77**	**1.79**	43.22	**<.01**	**0.57**	**1.13**

Note. Significant effects highlighted in bold (alpha-level adjusted for multiple hypothesis testing using Holm-Bonferroni correction; Holm, 1979).

As illustrated in Table 2, the analysis of skiing performance revealed a main effect for *gender* in both sprint and mass start competitions, indicating shorter lap times for female biathletes compared to male biathletes, which is a trivial finding given that females' course distances were shorter (see also Fig. 12). In addition, a significant main effect for *audience* was observed in mass start, indicating better performance in the presence (vs. absence) of an audience. Importantly, for both event types the main effects were qualified by significant two-way interactions between *gender* and *audience*. As illustrated in Figure 12, women performed worse (i.e., they skied slower) in presence (vs. absence) of an audience, whereas men performed better (i.e., they skied faster) in the presence (vs. absence) of an audience. This interaction was true for both sprint and mass start events.

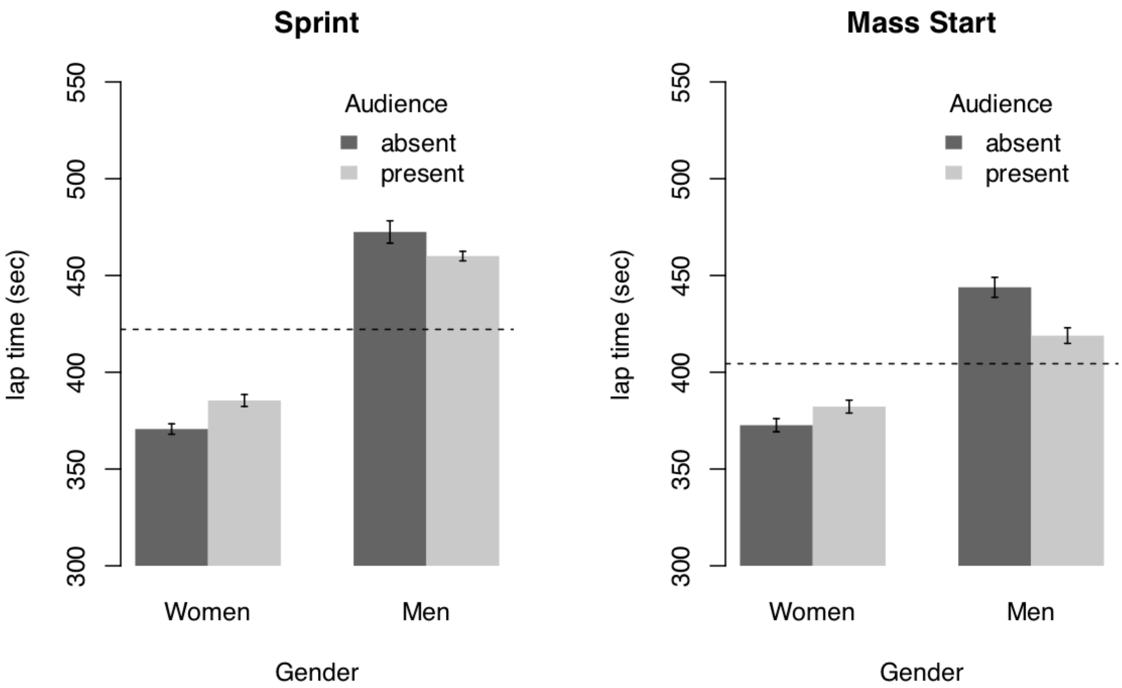

Figure 12. Lap times depending on the presence of an audience and athletes' gender, separately for sprint (left) and mass start (right) competitions. Error bars indicate 95% confidence intervals, dashed line indicates grand mean.

Shooting Time

Table 3. Results of the 2 x 2 x 2 ANOVA on shooting times in sprint and mass start

	Sprint Competitions				Mass Start Competitions			
Effects	*F* (1,81)	*p*	η_p^2	d	*F* (1,32)	*p*	η_p^2	d
Audience	0.47	.49	0.01	0.08	0.49	.49	0.02	0.12
Gender	21.31	**<.01**	**0.21**	**0.51**	<0.01	.99	0.00	0.00
Position	40.84	**<.01**	**0.34**	**0.70**	87.27	**<.01**	**0.73**	**1.60**
Gender x Audience	7.03	**.01**	**0.08**	**0.29**	5.54	**.03**	**0.15**	**0.40**
Gender x Position	13.92	**<.01**	**0.15**	**0.41**	16.22	**<.01**	**0.34**	**0.69**
Audience x Position	1.86	.18	.02	0.15	<0.01	.97	0.00	0.01
3-way Interaction	1.45	.23	.02	0.13	3.72	.06	0.10	0.33

Note. Significant effects highlighted in bold (alpha-level adjusted for multiple hypothesis testing using Holm-Bonferroni correction; Holm, 1979).

As shown in Table 3, analysis of shooting time revealed main effects of *position* (both competition formats: longer shooting time for prone compared to standing position) and *gender* (sprint: shorter shooting times for male compared to female athletes). Again, these main effects were qualified by a significant *gender x audience* interaction in both sprint and mass start races. This interaction indicated that women exhibited shorter (i.e., better) shooting times in the presence of an audience than in the absence of audience, whereas men showed longer (i.e., worse) shooting times in the presence (vs. absence) of an audience (see Figure 13).

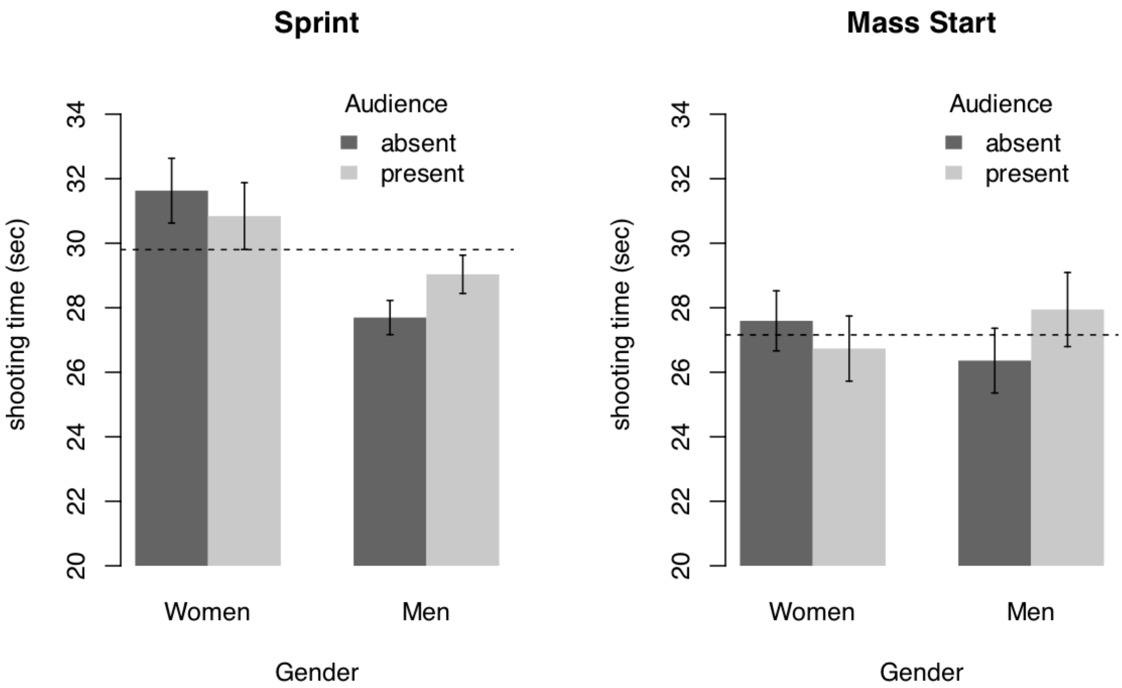

Figure 13. Shooting time depending on the presence of an audience and athletes' gender, separately for event type. Error bars indicate 95% confidence intervals, dashed line indicates grand mean.

Shooting Accuracy

Table 4. Results of 2 x 2 x 2 ANOVA to analyze shooting accuracy in sprint and mass start

	Sprint Competitions				Mass Start Competitions			
Effects	*F* (1,81)	*p*	η_p^2	d	*F* (1,32)	*p*	η_p^2	d
Audience	0.30	.58	0.00	0.06	3.34	.08	0.09	0.31
Gender	2.56	.11	0.03	0.18	0.25	.62	0.01	0.09
Position	39.59	**<.01**	**0.33**	**0.69**	9.00	**.01**	**0.22**	**0.51**
Gender x Audience	17.00	**<.01**	**0.17**	**0.45**	0.06	.82	0.00	0.04
Gender x Position	1.54	.22	.02	0.14	0.01	.91	0.00	0.02
Audience x Position	0.03	.87	.00	0.02	2.53	.12	0.07	0.27
3 way Interaction	0.81	.37	.01	0.10	1.28	.27	0.04	0.19

Note. Significant effects highlighted in bold (alpha-level adjusted for multiple hypothesis testing using Holm-Bonferroni correction; Holm, 1979).

In addition to the main effect for position, indicating higher shooting accuracy in prone shooting compared to standing shooting in both sprint and mass start competitions, analysis of shooting accuracy again revealed a two-way interaction between *gender* and *audience* in sprint competitions (see Table 4). As illustrated in Figure 14, female biathletes showed higher (i.e., better) shooting accuracy in the presence (vs. absence) of an audience. By contrast, male biathletes showed lower (i.e., worse) shooting accuracy in the presence (vs. absence) of an audience. This interaction was not found in mass start competitions. [5]

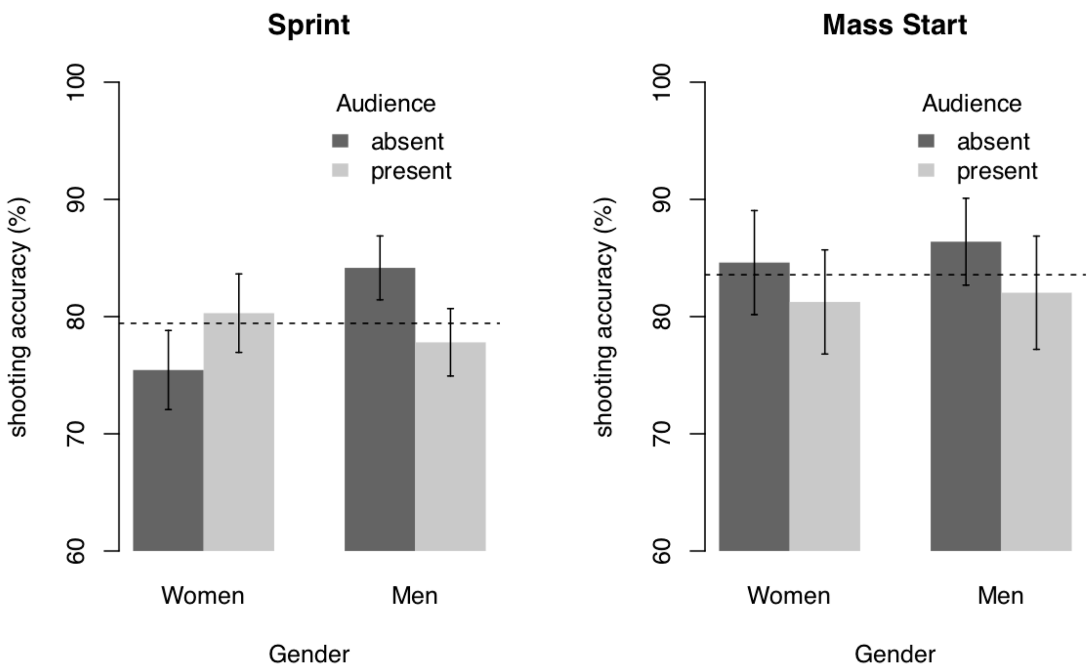

Figure 14. Shooting accuracy depending on the presence of an audience and athletes' gender, separately for event type. Error bars indicate 95% confidence interval, dashed line indicates grand mean.

[5] In addition to skiing and shooting performance, we analyzed overall biathlon performance (total course time from finish to start) for both sprint and mass start using separate 2 x 2 ANOVAs. Most importantly, it again revealed a significant interaction between gender and audience in both competition formats, (sprint: $F(1,81) = 29.622$, $p < .001$, $\eta^2 = .061$; mass start: $F(1,32) = 22.704$, $p < .001$, $\eta^2 = .217$), indicating longer (i.e. slower) course times for women with an audience present (vs. absent), but shorter (i.e. faster) course times for men in the presence (vs. absence) of an audience.

4.1.4 Discussion

The aim of the current study was to examine social facilitation effects (Allport, 1924; Zajonc, 1965) for different task types (Strauss, 2002) in an ecologically valid high performance setting. To this end, we analyzed the impact of an audience's presence vs. absence on elite biathletes' performance in World Cup competitions. The characteristics of biathlon combined with the forced lockdown measures during the Covid-19 pandemic provided the unique opportunity to dissociate task specific social facilitation effects (skiing = conditioning task, shooting = coordination task). In contrast to most studies on social facilitation theory, we measured actual behavior of elite athletes under real world conditions (i.e., World Cup competitions), thereby following a recent call to (re)focus on direct observation of actual behavior in psychological research (Baumeister, Vohs & Funder, 2007).

Given that we incorporated the factor gender solely to account for sport-specific differences between males' and females' official competition demands (course distances etc.) as well as performance differences (e.g., slower skiing and shooting speed of women compared to men, Luchsinger et al., 2018; Luchsinger et al., 2019), we did not put forward gender specific hypotheses concerning social facilitation effects in the first place. To our great surprise, the overwhelming majority of analyses showed a pronounced gender by audience interaction. Even more noteworthy, the direction of the gender by audience interactions differed systematically with the type of task (see Strauss, 2002).

In the *conditioning task* (i.e., cross-country skiing) performance was characterized by *social facilitation* in male biathletes as evidenced by shorter (i.e., faster) lap times in the presence (vs. absence) of an audience. By contrast, female biathletes performed worse (i.e., skied slower) in presence (vs. absence) of an audience, and hence showed the opposite effect of social facilitation, an effect that we suggest to call *social difficilitation*. This result held true for both sprint as well as mass start competitions. Consequently, performance enhancements in the presence of audience of male biathletes in the conditioning task are in line with previous research that is concluded in Strauss (2002). However, female athletes show the opposite pattern.

Interestingly, a reverse pattern of results was observed in the *coordination task*: biathlon shooting times were characterized by *social difficilitation* (i.e., longer shooting times) in male athletes in the presence (vs. absence) of an audience, whereas female athletes exhibited social facilitation effects (i.e., shorter shooting times) when an audience was present (vs. absent). Again, this significant interaction was found in both sprint and mass start analyses. Finally, these findings on shooting times were also largely mirrored in shooting accuracy, further bolstering the gender-specific differences within coordination tasks: Whereas males showed *social difficilitation*, as evidenced by less accurate shooting with an audience present (vs. absent), females showed *social facilitation* in sprint (but not mass start) competitions, as indicated by more accurate shooting with an audience present (vs. absent).[6]

Whereas previous research on social facilitation effects in coordination tasks is characterized by heterogeneous findings (Strauss, 2002), to the best of our knowledge, systematic gender differences in social facilitation have not been the topic of established research. Consequently, this leads to the following question: What might explain the surprisingly (and unpredicted) task-dependent opposite effects of an audience on elite male and female biathletes' performance?

As early as 1898, Triplett noted that girls seemed more positively affected by the presence of others than boys while performing a motor coordination task. However, this early observation has been largely ignored by researchers in the subsequent 120 years as gender differences have not been tested systematically. We therefore turned to Strauss (2002) comprehensive review on social facilitation effects in motor performance and screened all reviewed studies for gender bias in sample characteristics (see Beery & Zucker, 2011; Cundiff, 2012; Correa-de-Araujo, 2006). Excluding one double entry, the review includes 89 references. We gained access to 81 publications and consequently included 47 empirical papers into the analysis (excluding theoretical publications, reviews, meta-analyses, or data based on animals), published between 1889 and 1999. Together, these studies represent a total of 6144 participants.

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[6] Notably, the findings of faster shooting times and higher shooting accuracy for female athletes and the opposite pattern for males are in contrast to speed-accuracy trade-offs that have been observed, for instance, under high anxiety conditions and increased arousal in handgun shooting (Nieuwenhuys & Oudejans, 2010). This finding is in line with Beilock and colleagues (2008) who showed that these trade-offs may not apply to expert performers such as the participants of the current study.

Our analysis revealed a clear selection bias towards male participants in motor performance related social facilitation research: Two thirds (66 %) of the analyzed participants were male, whereas only 16 % were female (no explicit information about gender were provided for 18 % of the participants). Of the 47 empirical papers we analyzed, 19 (appr. 41 %) studies included exclusively male participants, 3 (6 %) included exclusively female participants, 12 (26 %) included both male and female participants, with 3 (6 %) reporting an equally balanced distribution of male and female participants. No information about gender distribution were provided in 10 (21 %) studies.

We conclude that this analysis suggests a clear selection bias in research on social facilitation theory. Sample selection bias results from non-random exclusion of certain observations and potentially threatens both internal and external validity of scientific work as results may not be generalizable (Heckman, 1979; Berk, 1983). The screened studies on social facilitation suggest that over one third (41%) of the investigations systematically excluded female participants. It follows that if our empirical findings together with the reported selection bias prove robust, then the validity and generalizability of social facilitation theory needs to be questioned. In fact, if our knowledge about social facilitation theory is for the most parts based on male participants, it may also explain the surprisingly (and theoretically unpredicted) task-dependent opposite effects of an audience on elite male and female biathletes' performance.

The obvious first consequence for future research is to consider balanced gender distributions in participants and explicitly address gender differences in social facilitation. A second consequence is that future research would be well advised to consider task- as well as gender-specific *social facilitation* and *social difficilitation* effects, thereby sparking an extension and further development of social facilitation theory.

Despite the fact that past research's gender selection bias may explain the unpredicted empirical data found in this study, the exact nature of the processes driving these effects remains to be determined. If one were to turn to established theories of social facilitation that highlight the role of changes in activation or in attentional processes, one would not expect gender specific effects in the first place (see meta-analyses by Bond & Titus, 1983; Uziel, 2007). However, stepping beyond the confines of social facilitation theories proper there is a plethora of well-known gender differences that may help to explain the current findings.

First, sex stereotypes and gender roles are likely to affect performance in sport (e.g. Hively & El-Alayli, 2014; for a review, see Chalabaev et al., 2013). For instance, men are known to perform better in sports that require strength, speed, or endurance which is reflected in the existence of corresponding sex stereotypes (Chalabaev et al., 2013). Following situational approaches within stereotype threat theory (Schmader, Johns & Forbes, 2008) that are based on the assumption of an individual's fear of being judged negatively based on a negative stereotype it would be conceivable that an audience could trigger stereotype threat. Consequently, women may perform worse in the conditioning task of cross-country skiing (out of fear to confirm a negative stereotype of women being inferior to men in this type of task), while males may increase their performance when being observed and evaluated. In contrast, men do not necessarily outperform women in coordination tasks such as shooting (as a case in point a woman won the Olympics in skeet shooting, Chalabaev et al., 2013; see also Goldschmied & Kowalczyk, 2016). Accordingly, a conceivable stereotype threat in biathlon triggered by the audience may enhance women's shooting performance but impair performance in men.

Second, women are seen to be more susceptible to feedback of others compared to men due to differences in self-construals: while men are mainly characterized by independent self-construal, women's self-construal is seen as interdependent, considering others as part of the self (Cross & Madson, 1997). If women experience the spectators' reaction to every single shot as encouraging, the presence of an audience may enhance shooting performance in general and count for the performance improvements. However, it is unclear how this notion might explain the reversed direction of audience effect in skiing performance.

Finally, men and women tend to differ in competitive attitudes (e.g., Niederle & Vesterlund, 2011) with males responding more positively to competition (e.g., competition improves running performance in boys; Gneezy & Rustichini, 2004). If one assumes these performance benefits in competitive conditioning tasks are partly due to increased arousal, activation theories of social facilitation might serve to explain task and gender specific social facilitation effects in biathlon. Recall that classic activation theories (Zajonc, 1965; Blascovich et al., 1999) posit that arousal benefits comparatively simple conditioning tasks, while being detrimental to comparatively complex, coordinative tasks. Therefore, increased arousal (due to audience) might benefit male performance in skiing, while being detrimental to shooting. In contrast, lower arousal of female biathletes might be detrimental for skiing, but beneficial for shooting. However, these approaches can only be seen as first attempts to explain the present findings. Currently, explaining these task and gender specific social facilitation effects is a topic for future research.

Finally, it should be noted that the present study design that is based on archival competition data under real world conditions did not allow to include additional factors that may moderate social facilitation effects such as personality characteristics (e.g. Uziel, 2007; Graydon & Murphy, 1995). This was also true for the consideration of specific training regimes that could have led to significant performance improvements, individual injuries or illness that occurred in the time gap between pre-pandemic competitions and competitions during the pandemic. However, we deem it improbable that (and actually cannot see how) these factors could account for the task-dependent findings that systematically differ between males and females.

As we argued in the method section, working with archival data imposed an upper limit on sample size. As highlighted by Button et al. (2013), small samples that produce significant results do not necessarily (and, in fact, are not very likely to) represent true population effects. In addition, given the lack of a priori power also the gender interaction might not replicate with larger samples. It follows that future and better powered research is needed to corroborate our findings.

Beside these limitations, the present work makes a significant contribution to the field of social facilitation for three main reasons: First, we examined first hand performance indicators in elite biathlon (i.e. skiing time, shooting accuracy, shooting time) instead of proxy variables employed by the majority of established work (e.g., single table tennis serve: Graydon & Murphy, 1995). Second, performance was observed in an ecologically valid, real-world context contrasting World Cup competitions featuring a real audience with those featuring empty ranks. This is in contrast to many existing studies, using confederates to mimic an audience in laboratory settings (e.g., audience consisting of 15 well known peers: Rhea et al., 2003). Finally, by relying on data provided by elite athletes the current study offers the benefit of studying social facilitation effects in situations where participants' motivation to perform at their best can be taken for granted – in contrast to the majority of research employing recreational athletes (e.g., Bell & Yee, 1989; Dube & Tatz, 1991) or students (e.g., Rhea et al., 2003). In closing, the present work calls for future research on the one hand to further validate these findings by means of replications with higher statistical a priori power (e.g., in experimental settings systematically varying both gender and task type) and on the other hand to focus on the exact processes and mechanisms that drive those effects.

4.2 The Impact of Co-Acting Competitors on Shooting Performance in Elite Biathletes

Chapter 4.2 was submitted for publication as:

Heinrich, A., Köhler, H., Müller, F., Stoll, O., & Cañal-Bruland, R. (submitted). The impact of co-acting competitors on shooting performance in elite biathletes.

Abstract

Objectives: Grounded in social facilitation theory, this study examined the impact of co-acting competitors (i.e., opponents) on elite biathletes' shooting performance based on World Cup competition data. To this end, the impact of the number of as well as the mean overlapping time with co-acting competitors at the shooting range on both shooting time and shooting accuracy was assessed.

Design and Methods: Competition data of World Cup races from 2005 to 2020 were analyzed. This included 115 mass start and 195 pursuit events of a total of 758 elite biathletes amounting to 57.251 shooting bouts equivalent to a total of 286.255 shots. The data was analyzed using a multilevel approach.

Results: Results revealed two main findings: First, the more co-acting competitors present at the shooting range, the higher was shooting accuracy. There was no effect of number of co-acting competitors on shooting time. Second, the more time overlapped with co-acting competitors, the more negatively affected was biathletes' shooting performance (i.e., longer shooting times and lower shooting accuracy).

Conclusions: The present study provides first evidence that the co-action of opponents – both in terms of number of opponents as well as overlapping time during shooting – influence elite biathletes shooting performance.

4.2.1 Introduction

In elite biathlon, performance is influenced by several factors including physiological (e.g., Rundell & Bacharach, 1995; Stoeggl et al., 2015; Laaksonen et al., 2020) and biomechanical determinants (e.g., Baca & Kornfeind, 2012; Sattlecker et al., 2014; Köykkä et al., 2020; Sadowska et al., 2019). In addition, psychological determinants such as attentional processes (e.g., Gallicchio et al., 2016; Luchsinger et al., 2016; Heinrich et al., 2020) and coping with performance pressure impact performance (Vickers & Williams, 2007; Lindner, 2017). While there is considerable research on biological and psychological factors determining biathlon performance (for a review, see Laaksonen et al., 2018), work on the impact of social context e.g., the presence vs. absence of an audience (Heinrich et al., 2021a) or supportive vs. non-supportive fans (Harb-Wu & Krumer, 2019) on biathlon performance is scarce (Heinrich et al., 2021b). To the best of our knowledge, there are only two exceptions to this lacuna.

First, Harb-Wu and Krumer (2019) examined effects of a supportive vs. non-supportive audience in biathlon by analyzing archival competition data. Specifically, they compared both shooting and skiing performance of biathletes in competitions abroad (non-supportive audience) vs. their home countries (supportive audience). Results showed an impact of supportive vs. non-supportive audience that was further moderated by World Cup ranking and type of task: Top-ranked biathletes' shooting accuracy deteriorated (i.e., more missed shots) in front of a supportive audience; lower-ranked athletes showed no effects in shooting performance, but improved their skiing performance (i.e., skied faster in front of a supportive audience), thereby providing first evidence that social context influences biathlon performance.

Second, Heinrich and colleagues (2021a) recently tested whether the mere presence vs. absence of an audience in biathlon would impact elite biathletes' performances. The absence of spectators due to COVID-19 pandemic restrictions in 2020 was used to analyze audience effects on both skiing and shooting performance in real World Cup competitions based on archival data. Results confirmed that the presence of spectators indeed influences biathletes shooting and skiing performance. These effects were task- and gender-specific. That is, in the presence of an audience male biathletes showed improvements in skiing performance (i.e., skied faster) but deteriorations in shooting (i.e., shot worse). In contrast, female athletes showed the reverse pattern (i.e., they skied slower but improved their shooting).

Heinrich et al. (2021a) explained these task-specific differences in the context of *social facilitation* theory (Allport, 1924; Zajonc, 1965) positing that the presence of others affects – typically in a positive direction – cognitive or motor performance. This theoretical approach has inspired a plethora of studies, for instance, on the effects of an audience's presence (see Martens, 1969; Cottrell et al., 1968; Haas & Roberts, 1975; for an overview, see Strauss, 2002) or its specific behavior (supporting vs. non-supporting; e.g., Epting et al., 2011). However, its applications in studying determinants of biathlon performance are limited to the two mentioned studies (i.e., Heinrich et al., 2021a; Harb-Wu & Krumer, 2019).

While the latter two studies are noteworthy for providing first insights into the impact of social context on biathlon performance, the impact of co-acting competitors on biathlon performance has been neglected thus far. This is surprising given that more than 120 years ago in social facilitation theory's pioneering study, Triplett (1898) examined cycling performance in the presence vs. absence of *co-acting* cyclists. Results indicated performance improvements in the presence of other competitors relative to performing individually.

Building on these pioneering findings, the present study sought to test whether similar effects of co-actors' presence on biathletes shooting performance are evident in elite biathlon competitions. Biathlon provides a unique testbed, first, due to its clearly structured competition format. That is, biathletes perform their shooting in a special area, the so called shooting range, characterized by equally spaced firing lanes numbered in ascending order. During competition biathletes take position in a given firing lane and perform shooting bouts of five shots. During this time window, there may be co-acting competitors present in the neighboring lanes whose shooting bouts temporally overlap. Second, because all relevant parameters such as the competition format, firing lane, the beginning and end of a biathlete's shooting bout, as well as achieved performance are measured and collected at World Cup competitions by the International Biathlon Union (IBU), these particular data provide an ideal opportunity for testing the impact of co-acting competitors (i.e., their number and their temporal overlap) on biathletes' performance.

This study aimed at examining whether previously documented performance improvements due to the presence of co-acting others (e.g., Triplett, 1898) also influence biathletes' shooting performance. To this end, we analyzed archival data of biathlon World Cup competitions spanning the years 2005 to 2020 from both mass start and pursuit competitions concerning the impact of co-actors on indicators of athletes' shooting performance. This included data of 115 mass start and 195 pursuit events of a total 758 elite biathletes amounting to 57.251 shooting bouts equivalent to a total of 286.255 shots.

4.2.2 Methods

Archival Competition Data

All analyses were based on competition data available at the International Biathlon Union (IBU) datacenter (International Biathlon Union, 2021c), collected by the official time keeping company for international IBU-competitions in biathlon (SIWIDATA GmbH, Merano, Italy). Permission to use the data for scientific purposes was given by the IBU. We focused exclusively on mass start and pursuit World Cup events that took place between 2005 and 2020 (for details, see below).

Mass Start. Mass start competitions represent a head-to-head competition format as all athletes (typically 30 biathletes consisting of the 25 highest ranking athletes in the World Cup and five additional athletes who earned the most World Cup points at the mass start's competition weekend) start at the same time. Hence, an athlete's position on the skiing course (women: 12.5 km, men: 15 km) always corresponds to the overall ranking (i.e., sequence of reaching the finish equals ranking). The skiing course is divided into five laps with four shooting blocks in between these laps. One shooting block requires five shots at five horizontally aligned targets from a shooting distance of 50m. The first two shooting bouts are performed in prone position (target diameter: 4.5 cm), the two subsequent bouts in standing position (target diameter: 11.5 cm). For every missed target, athletes have to complete an additional penalty lap of 150 m (for regulatory details, see International Biathlon Union, 2020b).

Pursuit. Athletes in pursuits start sequentially, that is, with a delay based on the results of a previous competition (typically sprint). This head-to-head racing format features a higher number of athletes, including the 60 highest ranked athletes of the previous competition. The to-be-skied distance (women: 10 km, men: 12.5 km) also spans five laps, and both number of shooting bouts and sequence of shooting position as well as target diameters are similar to mass start competitions. Similar to mass start, missing a target adds an additional 150 m penalty lap to the athletes' course (International Biathlon Union, 2020b).

Data Analysis

Data Preparation. First, we selected all mass start and pursuit competitions of World Cup competitions in the years 2005-2020. For the year 2020, however, we excluded one mass start competition that took place without an audience due to COVID-19 pandemic as the presence of an audience has previously been shown to systematically impact shooting (and skiing) performance (for details, consult Heinrich et al., 2021a). Second, we carefully screened all data regarding the correct numbers of laps and shooting blocks and consequently excluded one World Cup event as it contained an incorrect number of laps. Third, data screening revealed that a subset of recorded shooting blocks contained single missing values for shooting accuracy (5.28% of all recorded single shots), even though shooting times were available for these shots. Following up on this issue with a representative of SIWIDATA (i.e., the company responsible for IBU competition protocols) revealed that missing shooting data is most commonly due to either a miss going astray the target area or errors due to crossfire. We consequently treated missing data as misses (i.e., shots not hitting the target). In addition, a very small subset of shooting bouts did not contain information for all five shots in both shooting time and shooting accuracy (0.12% of all recorded shooting blocks) and was consequently excluded. Based on these data, shooting accuracy was then computed as the relative frequency of hits for every shooting block. Additionally, we calculated World Cup points for both mass start and pursuit competitions for every year and every athlete based on the rankings in every single competition following the official rules for World Cup discipline points (International Biathlon Union, 2020b). After data preparation, data contained 115 mass start and 195 pursuit competitions of 758 biathletes (373 males, 385 females), amounting to 57.251 shooting blocks (286.255 single shots).

Measuring Co-Acting. To quantify the degree of co-acting for each athlete we analyzed the presence of co-acting competitors for every athlete in each shooting block. To consider both the number of co-acting competitors but also the temporal overlap of their presence with the biathlete in question, we calculated two variables. First, we calculated the number of competitors co-acting during the time the biathlete was at the shooting mat. Second, we calculated the mean temporal overlap (in seconds) of the co-acting biathletes with the athlete in question.

Statistical Tests. As the data have a hierarchical two-level structure (i.e., shooting blocks nested in athletes), we applied a multilevel approach without running random effects[7] of the main predictors on the dependent variables which enabled us to separate the variance within one athlete from the variance between athletes (Finch, Bolin & Kelley, 2014).

Given the aim of the present study, we first included the two main predictors *opponents present* (i.e., number of present opponents) and *mean overlap* (i.e., the mean temporal overlap with co-acting competitors) into a basic multilevel-model for the two dependent variables *shooting time* and *shooting accuracy* with specification of a random intercept. Subsequently, we followed a stepwise approach to include those additional predictors in the data set yielding the highest increase in AIC for the dependent measures shooting time and shooting accuracy (Yamashita et al., 2007). Specifically, the following additional predictors likely to affect shooting performance in biathlon were considered in the stepwise procedure: World Cup points *(WC points)* were included to analyze shooting performance differences in biathletes (see Luchsinger et al., 2018; Luchsinger et al., 2019). The number of the current shooting block *(shooting block)* served to test the effects of accumulated workload during competitions (see Heinrich et al., 2020). This variable also indirectly represents shooting position (first and second shooting block: prone position; third and fourth shooting block: standing position; see e.g., Luchsinger et al., 2018). *Event*

7 We did not run random effects as we did not analyze the effect's variance but controlled for variance between athletes. When running random effects, the model no longer converged.

type (i.e., pursuit or mass start) was included to analyze differences between competition formats. *Gender* (i.e., male or female; see Luchsinger et al., 2018; Luchsinger et al., 2019) served to model performance differences between women and men. Finally, both *shooting accuracy* and *shooting time* also served as predictors, albeit only for the analysis where they were not the dependent variable (i.e., shooting accuracy for predicting shooting time and shooting time for predicting shooting accuracy).

4.2.3 Results

Before describing the results of the two multilevel-models, descriptive statistics for the dependent measures and the main predictors are provided. To start with the former, biathletes' performance was characterized by a mean shooting time of 31.00 s (SD = 6.10 s) and mean accuracy of 82 % (SD = 18.8 %) per shooting block. On average, 17 opponents (SD = 8) were present at the shooting range when an athlete was completing a shooting block and the mean overlapping time with those opponents standing on the shooting mat was 1.7 s (SD = 1.48 s).

Shooting Time

Table 5. Results of the multilevel analysis on shooting time

	Coefficient	*p*-Value	Standardized Coefficient
Intercept	32.390	<0.001	-0.410
Opponents Present	-0.006	0.182	-0.009
Mean Overlap	0.932	<0.001	0.230
WC Points	-0.003	<0.001	-0.070
Shooting Block 2 (vs. Block 1)	2.331	<0.001	0.380
Shooting Block 3 (vs. Block 1)	-0.881	<0.001	-0.140
Shooting Block 4 (vs. Block 1)	-0.674	<0.001	-0.110
Shooting Accuracy	-6.009	<0.001	-0.180
Event Type: Pursuit (vs. Mass Start)	2.565	<0.001	0.420
Gender: Male (vs. Female)	-2.390	<0.001	-0.390

As illustrated in Table 5, the predictors mean overlap and WC points turned out to contribute significantly to shooting time, while the predictor opponents present did not. Furthermore, all additional predictors of this model were significant. Table 5 reports coefficients, *p*-values as well as standardized coefficients in predicting shooting time. To facilitate the interpretation of the coefficients, we briefly translate and put each regression coefficient in context: First and foremost, an increase of 1 s in overlapping time with co-acting competitors was linked with an average of 0.93 s longer shooting time. In other words, if the mean overlapping time with co-acting athletes at the shooting range increased by the observed standard deviation of 1.48 s, shooting time was predicted to be 1.38 s longer (1.48 x 0.93). Second, an increase of one WC point was associated with an on average 3 milliseconds faster shooting. Consequently, the model predicts that the difference in shooting time between the best and worst performing athletes (650 vs. 0 WC points) would be 1.95 s (650 x -0.003). Third, the number of shooting blocks explained variance in shooting time with a mean increase of 2.33 s in the second shooting bout compared to the first bout (both in prone position), but a decrease of 0.88 s in the third and 0.67 s in the fourth shooting bout (i.e., faster shooting compared to the first shooting block; both shooting blocks in standing position). Fourth, the model predicts that biathletes with 100 % shooting accuracy are shooting 6.01 s faster compared to 0 % shooting accuracy. Fifth, pursuit competitions were related to an average of 2.57 s longer shooting times compared to mass start events. Finally, male biathletes showed on average 2.39 s shorter shooting times than female athletes.

Shooting Accuracy

Table 6. Results of the multilevel analysis on shooting accuracy

	Coefficient	*p*-Value	Standardized Coefficient
Intercept	1.078	<0.001	0.250
Opponents Present	0.001	<0.001	0.040
Mean Overlap	-0.007	<0.001	-0.060
WC Points	0.000	<0.001	0.100
Shooting Block 2 (vs. Block 1)	0.0147	<0.001	0.080
Shooting Block 3 (vs. Block 1)	-0.072	<0.001	-0.380
Shooting Block 4 (vs. Block 1)	-0.069	<0.001	-0.370
Shooting Time	-0.008	<0.001	-0.250
Gender: Male (vs. Female)	-0.020	<0.001	-0.100
Event Type: Pursuit (vs. Mass Start)	-0.001	0.656	-0.007

As illustrated in Table 6, all entered predictors turned out to significantly predict shooting accuracy. To start with the main predictors, shooting accuracy increased with the number of co-acting competitors (opponents present): The co-action of one additional biathlete at the shooting range was related to 0.1 percentage-points higher shooting accuracy. In contrast, the regression coefficient of overlapping time indicates that for every increase of 1 s in time overlap with co-acting competitor, mean shooting accuracy was 0.71 percentage-points lower. Similar to shooting time, a positive relationship between WC points and shooting performance was also found for shooting accuracy: An increase of one WC point was associated with on average 0.014 more percentage-points in shooting accuracy. Consequently, the model predicts a difference of 9.1 percentage-points in shooting accuracy between the best and worst performing athletes (650 vs. 0 WC points). The second shooting bout was predicting an increase in shooting accuracy of 1.5 percentage-points when compared to the first shooting block (both in prone position) while shooting blocks 3 and 4 (both in standing position) were associated with mean decreases of 7.2 and 6.9 percentage-points when compared to the first shooting bout. Additionally, an increase of 1 s in shooting time was associated with an on average 0.77 percentage-points lower shooting accuracy. Finally, and in contrast to shooting time, women outperformed men in shooting accuracy as male biathletes showed an average of 2 percentage-points lower shooting accuracy compared to female athletes.

4.2.4 Discussion

The present study examined the impact of co-acting competitors on shooting performance in elite biathletes, grounded in social facilitation theory (Allport, 1924; Zajonc, 1965). Next to social context, the archival competition data set allowed to include additional variables (e.g., World Cup points, gender, competition format).

Number of Co-Acting Competitors and Shooting Performance

Results showed that a higher number of co-acting competitors increase shooting accuracy. In this regard, an increase by the observed standard deviation of eight co-acting competitors is related to a 0.8 percentage-points increase in shooting accuracy, corresponding to about one additional hit in every sixth competition. This finding is in line with the observations in Triplett's (1898) seminal study where the presence of other co-acting athletes yielded performance improvements. However, while Triplett's cycling task represents an example of a so called conditioning task, the biathlon shooting performance represents a so called coordination task (see Strauss, 2002, for a detailed discussion). As pointed out by Strauss (2002), social facilitation effects have been repeatedly documented in conditioning tasks, but findings are more heterogeneous in coordination tasks. Therefore, the current findings add support to the notion that social facilitation effects may also influence experts' performance in coordination tasks (Haas & Roberts, 1975; Dube & Tatz, 1991).

In contrast to shooting accuracy, the number of co-acting biathletes was not related to shooting time. Note though, that in determining overall biathlon performance, shooting accuracy is the far more important contributor because each miss is heavily penalized by a penalty lap (its impact has been estimated to be 10 x higher; see Luchsinger et al., 2019). Consequently, one can speculate that biathletes primarily focus on shooting accuracy rather than on shooting time which is also mirrored in the present findings. The higher importance of shooting accuracy compared to shooting time is further corroborated by performance differences based on World Cup points. While the difference between the best and worst performing athletes (650 vs. 0 World Cup points) is associated with a 9.1 percentage-point higher shooting accuracy (corresponding to almost two additional hits in a given mass start or pursuit competition), it is associated with only 1.95 s shorter shooting times.

Overlapping time with co-acting competitors and shooting performance

In contrast to the number of co-acting competitors, higher overlapping time with athletes co-acting was negatively related to shooting accuracy. More specifically, an increase of 1 s in overlapping time with co-acting competitors was related to a 0.71 percentage-points lower shooting accuracy. As mean overlapping time measured on average 1.7 s with a standard deviation of 1.48 s, an increase in overlapping time by one standard deviation is related to approximately one additional miss in every fifth competition. Interpreted in the light of social facilitation theory, performance decrements in coordination tasks are related to attentional exhaustion (Baron, 1986), interfering dominant responses (Zajonc, 1965), or threat rather than challenge (Blascovich et al., 1999). Based on the current findings it is conceivable that longer time overlap with co-acting competitors may trigger these attentional processes and consequently result in decreased shooting accuracy. In contrast to time overlap, one could speculate that a higher number of co-acting competitors might involve an exclusive focus on relevant stimuli (*overload hypothesis;* Baron, 1986) and hence result in performance enhancements (see previous section).

An increase in overlapping time was also associated with performance decrements in shooting time (i.e., longer shooting times) as an increase of overlapping time by one standard deviation (1.48 s) is associated with 1.38 s longer shooting time. However, this result has to be interpreted with caution as overlapping time with co-competitors is likely to be confounded with shooting time (i.e., if athletes need more time at the shooting mat this results in a higher time overlap with others). To summarize, longer temporal overlap with co-acting competitors was associated with negative effects on both shooting time and accuracy (in contrast to the previously reported positive effects of increasing numbers of present co-actors).

Additional Predictors of Shooting Performance

Shooting Block. In addition to the co-acting variables, a number of additional predictors were related to shooting performance. In this regard, our findings corroborate previous results of longer shooting time with accumulating physiological workload (see Heinrich et al., 2020) for prone position (first and second shooting block; similar tendency in standing shooting). In contrast, shooting accuracy was increasing with increasing number of shooting blocks in both prone and standing position. This result contradicts previous experimental studies either revealing decreased shooting accuracy with increasing workload (e.g., Vickers & Williams, 2007; Ihalainen et al., 2018) or showing no effects (Luchsinger et al., 2016; Gallicchio et al., 2016). As previous competition data analyses predominantly focused on performance on competition level instead of shooting block level (e.g., Skattebo & Losnegard, 2018; Luchsinger et al., 2018), these results provide new insights that may have practical implications as concerns the improvement of shooting performance.

Shooting Time and Shooting Accuracy. Our findings support previous analyses of shooting in expert biathletes (Lindner, 2017) showing that higher shooting accuracy is related to shorter shooting times, thereby arguing against potential speed-accuracy trade-offs (see Nieuwenhuys & Oudejans, 2010 for speed-accuracy trade-offs in shooting; for counterevidence in expert performers, see Beilock et al., 2008).

Gender Differences. The observed gender differences with men outperforming women in shooting time support analyses of archival biathlon data in other competition formats (sprint: Luchsinger et al., 2018; Heinrich et al., 2021a; individual: Luchsinger et al., 2019). However, the finding of higher shooting accuracy in women in the present head-to-head competitions mass start and pursuit contradicts previous studies revealing on the one hand no gender differences in shooting accuracy in biathlon sprint competitions (Luchsinger et al., 2018; Heinrich et al., 2021a), but also in mass start competitions featuring a much smaller number of observations (Heinrich et al., 2021a), and on the other hand 1.6 more percentage-points in shooting accuracy in top ranked male biathletes compared to females in individuals (Luchsinger et al., 2019).

Competition Format. Finally, mass start competitions are related to shorter shooting times compared to pursuit competitions as the latter competition format forecasts 2.57 s slower shooting, while no differences in shooting accuracy were observed. These performance differences might be explained by the more exclusive sample in mass start competitions (see methods section).

Conclusion

To conclude, the present study provides first evidence for the impact of co-acting competitors – both in terms of number of opponents as well as overlapping time during shooting– on shooting performance in elite biathletes. On the one hand, a higher number of co-acting competitors were associated with higher (i.e., better) shooting accuracy which is in line with social facilitation effects of co-acting competitors (Triplett, 1898), but did not affect shooting time. On the other hand, the more time overlapped with co-acting competitors, the more negatively affected was biathletes' shooting performance (i.e., longer shooting time and lower shooting accuracy).

5 General Discussion

5.1 Theoretical Discussion

The central aim of the current dissertation project was twofold: 1) to contribute to our understanding of biathlon performance by applying an interdisciplinary approach and focusing on biological and psychological factors in conjunction, and 2) to integrate social context into a framework to explain and predict biathlon performance by examining the role of audience and the presence of co-competitors for biathlon performance applying a biosocial approach.

As outlined in Chapter 1.3 (see Heinrich et al., 2021), this endeavor was based on two main reasons. First, even though biological determinants and psychological factors of biathlon performance always occur in conjunction, so far research in biathlon has mostly looked at these factors in isolation. Consequently, I aimed at applying an interdisciplinary approach that allows to concomitantly examine biathlon performance from a biological and a psychological viewing angle. By doing so, I additionally addressed methodological issues of past research concerning ecological validity and representative task design. Second, the role of social context on biathlon performance has largely been neglected thus far. Hence, I addressed this research gap by focusing on social context, taking again an interdisciplinary approach into account and combining biological factors and social context.

5.1.1 Biopsychological Factors to Explain and Predict Biathlon Performance

Applying an interdisciplinary approach, I was especially interested in the role of focused attention (operationalized as gaze behavior) for successful biathlon shooting as well as the impact of physiological workload (i.e., biological determinant) on both these psychological processes and shooting performance.

Impact of Physiological Workload on Shooting Performance

To start with the latter aim, together with the co-authors of this study I examined the impact of physiological fatigue on both shooting time and shooting accuracy in an experimental setting (see Chapter 3.1). With the inclusion of shooting time we extended previous work that focused exclusively on shooting performance (with the only exception of Ihalainen at al., 2018). In addition, both shooting positions were included while past research investigated the impact of physiological workload exclusively on shooting performance in standing position, neglecting prone shooting (again with one exception: Hoffman et al., 1992). Further methodological extensions made in the study in order to provide an ecologically valid setting are discussed in Chapter 5.2.

In line with Ihalainen et al. (2018), the study revealed an increase in shooting times (i.e., time spent on shooting mat) with increasing workload level in athletes of both expertise level (i.e., elite and sub-elite biathletes) and hence performance decrements through physiological workload. These findings of the experimental study (Chapter 3.1) were corroborated when applying a big data approach and analyzing archival competition data in Chapter 4.2. Even if this study predominantly aimed at examining social aspects of biathlon performance, it additionally revealed increasing shooting times with an increased number of absolved shooting blocks in prone position (first and second shooting block; similar tendency in standing shooting).

Furthermore, shooting time seems to be a reliable factor to distinguish between expertise levels as elite athletes performed their shooting blocks significantly faster compared to sub-elite athletes (Chapter 3.1; in line with competition analyses between juniors and seniors of Kreivėnaitė, 2012). Consequently, it appears to be a reasonable goal to focus on shooting time when aiming elite level in biathlon.

In contrast to shooting time, increasing physiological workload did not affect shooting accuracy (i.e., percentage accuracy) in the experimental study (Chapter 3.1). The lack of an effect of workload level on shooting accuracy was also mirrored in radial error and aiming trace speed. When analyzing competition data and focusing on the number of shooting blocks (see Study 3, Chapter 4.2) instead of systematically increasing workload in an experimental setting, shooting accuracy even increased with increasing number of shooting blocks in both prone and standing position.

In this regard, the findings of Study 1 corroborate the results of Luchsinger et al. (2016), Gallicchio et al. (2016) and Gallicchio et al. (2019), but are in conflict with several other studies reporting a deterioration of shooting accuracy with increasing cardiovascular load (Hoffman et al., 1992; Grebot et al., 2003; Ihalainen et al., 2018; Vickers & Williams, 2007). One central approach to explain the inconsistent findings is the large heterogeneity concerning the applied methods with respect to participants' expertise level (e.g., percentage hit rate between 42% in Vickers & Williams, 2007, vs. 81% in Gallicchio et al., 2016), induced physiological workload (e.g., duration, intensity and type of task such as cycling ergometer vs. roller skiing) as well as assessment and ecological validity of shooting accuracy (e.g., simulated shooting task vs. real biathlon shooting). These substantial methodological differences are summarized in the closing of Chapter 1.2.1 and further discussed in the methodological discussion (Chapter 5.2). The result of increased shooting accuracy with increasing number of shooting blocks when analyzing World Cup competition data (Chapter 4.2) provides novel insights into shooting performance throughout a biathlon competition and highlights the ability of expert biathletes to not only maintain but even improve shooting accuracy under conditions of high physiological load. However, this finding has to be interpreted with caution in the context of the listed studies as most of them systematically increased cardiovascular load in an experimental setting while our study analyzed the number of shooting block in competition data.

While the discussion of the results in Chapter 3.1 is mainly based on biathlon-specific literature and methodological explanations for the conflicting findings with previous work (see also Chapter 5.2), the question arises of *why* one would theoretically predict an impact or no effect of physiological workload on shooting accuracy in biathlon. In this regard, one of the most prominent theories that potentially allows us to derive predictions might be the Yerkes-Dodson Law (Yerkes & Dodson, 1908), also referred to as the theory of the inverted U-hypothesis. This theory posits that with increasing levels of arousal, for instance exercise-induced arousal, performance first increases up until an optimal turning point at intermediate intensity levels, which is then followed by a decrease in performance until maximal intensity levels are reached. The inverted U-hypothesis is supported by reviews about effects of exercise-induced arousal on cognitive task performance (e.g., Gutin, 1973;

Weingarten, 1973; Tomporowski & Ellis, 1986) as well as meta-analyses (e.g., Etnier et al., 1997; Lambourne & Tomporowski, 2010; Chang et al., 2012). These analyses, however, additionally highlight the complexity of this relationship as the intricate link between exercise and cognitive performance is moderated by a variety of factors such as participants' fitness level and type of cognitive task (Etnier et al., 1997), timing of cognitive task administration and type of exercise (Lambourne & Tomporowski, 2010) as well as duration and intensity of exercise (Chang et al., 2012). The dependency of the effect that physiological workload has on perceptual-cognitive performance from type of task (i.e., working memory vs. attention/perception tasks) and, in addition, other factors, such as the level of expertise, is further corroborated by a recent review by Schapschröer and colleagues (2016). Even if the test procedure of the study presented in Chapter 3.1 included four workload levels and competition data analysis included 4 shooting blocks (Chapter 4.2), these levels were confounded with shooting position and do not allow for the evaluation of a quadratic pattern like the inverted-U. Consequently, the systematic examination of these factors from the theory of the inverted-U, thereby extending the theory and improving our theoretical understanding of the relationship between physiological workload and shooting performance, will be a fruitful route for future research.
Interestingly, while elite and sub-elite athletes differed in their shooting time (Chapter 3.1), they showed no differences in shooting accuracy that consequently does not seem to be an appropriate factor to distinguish between these expertise levels. Given these findings, one could speculate that less experienced biathletes (i.e., sub-elite) follow a speed-accuracy trade off (e.g., Hick, 1952; see Nieuwenhuys & Oudejans, 2010, for speed-accuracy trade-offs in handgun shooting) and accept slower shooting times to achieve high shooting accuracy - a loss in speed that disappears with higher expertise level.

Role of Gaze Behavior for Successful Biathlon Shooting Under Physiological Workload

As I strived to look at biological factors and psychological determinants in conjunction to contribute to our knowledge in explaining and predicting biathlon performance, I further examined the role of focused attention (operationalized as gaze behavior) for successful biathlon shooting and assessed how this psychological determinant is affected by physiological fatigue (see Chapter 3.1). To be able to implement this research aim, the co-authors and I first developed and validated an Eye Tracking system for the purposes of biathlon shooting (Chapter 2.3).

Based on previous findings that highlighted the importance of focused attention (Gallicchio et al., 2016; Luchsinger et al., 2016) and, in particular, a significant relationship between final fixation durations and shooting accuracy (with a medium effect size, i.e., the longer, the better; Vickers & Williams, 2007), we assumed that long final fixations as specific gaze behavior might be beneficial for successful biathlon shooting. However, when aiming at conceptually replicating previous work by Vickers and Williams (2007), we did not find any correlation between duration of final fixation and shooting accuracy. As we aimed to address several methodological issues of Vickers and Williams study (2007), a number of methodological differences may account for the divergent findings and are discussed in Chapter 5.2. Despite these methodological differences, the results are in contrast to several studies linking long Quiet Eye duration to high expertise and/or successful performance in different sport such as shotgun shooting (Causer et al., 2010), basketball (Vickers, 1996a; Rienhoff et al., 2015), billiard (Williams et al., 2002) or archery (Gonzalez et al., 2017a). Nevertheless, the present findings are in line with some studies raising doubts about the robustness of this phenomenon (e.g., Fischer et al., 2015; Querfurth et al., 2016). In addition, the mechanisms underlying Quiet Eye are not fully understood yet (see Gonzalez et al., 2017b, for an overview of theories). To sum up, the present study did not corroborate the importance of long final fixations for biathlon performance. Furthermore, we argue that athletes may develop individual optimal gaze behavior that is related to successful biathlon shooting as we observed large differences in individual fixation behavior that are reflected in fixation durations between 950ms and 4000ms –both at 100% accuracy level (see Chapter 3.1, Figure 11).

While Vickers and Williams (2007) concluded a general decrease of the duration of final fixation with increasing workload level and emphasized the importance of even increasing rather than decreasing final fixation duration under high workload and pressure situations to prevent choking under pressure, our results revealed no changes in gaze data with increasing workload level in both elite and sub-elite biathletes. While these results are also in contrast to Gallicchio et al. (2016) who reasoned decreases in focused attention through physiological workload based on reduced frontal-midline theta power, they are yet in line with Luchsinger and colleagues (2016) who did not find any effects of physiological workload on electroencephalographic activity – independent of expertise level. Thus far, research on focused attention under the specific conditions of biathlon is scarce and it consequently seems too early to draw final conclusions. Hence, the present results can rather be seen as a starting point to question the impact of physiological workload on gaze behavior in biathlon.

Finally, final fixation durations in standing shooting were shorter when compared to prone shooting. As previous work exclusively focused on standing shooting, this finding represents a novel contribution to the field. However, the differences between prone and standing position are not significant for relative final fixation (measuring final fixation duration independent of shooting time, built by the quotient of mean duration of final fixation and shooting sequence duration) so we argue that the duration of final fixation correlates with the time duration of the shooting block.

Conclusion Regarding Biopsychological Factors

To sum up, the present work provides novel insights into the intricate link between physiological workload, gaze behavior and shooting performance, thereby building interdisciplinary bridges and applying a biopsychological approach. First and foremost, results indicate that expert biathletes are able to maintain or even increase shooting accuracy under tremendous physiological workload but suffer regarding shooting time. In addition, shooting time but not shooting accuracy emerged as a reliable factor to differentiate between athletes' expertise level. Finally, and in contrast to previous work, the duration of final fixation did not appear to be relevant for successful biathlon shooting and was – similar to shooting accuracy – not affected by increasing physiological fatigue.

5.1.2 Biosocial Factors to Explain and Predict Biathlon Performance

As the impact of social context on biathlon performance has largely been neglected thus far (with one exception: Harb-Wu & Krumer, 2019), I proposed to integrate this aspect into a biopsychosocial framework to explain, predict and consequently optimize performance in biathlon (see Chapter 1.3). Based on this framework, I aimed to examine the role of social context by building an interdisciplinary bridge between social aspects and biological determinants (in specific: skiing and shooting performance). As a first step, the co-authors of Study 2 and I analyzed the impact that the presence vs. absence of audience might have on biathlon performance. In a second step, we focused on the social situation at the shooting range created by the presence of co-competitors and its role for successful shooting performance. In contrast to the methodological approach applied in the psychobiological study (Chapter 3.1) including a complex experimental set-up to examine physiological workload and gaze behavior in 23 expert biathletes, here we analyzed archival competition data provided by the International Biathlon Union (IBU). Regarding the first step, various lockdown measures that followed in the wake of the COVID-19 pandemic offered the unique opportunity to compare competition data on Biathlon World Cup events that were held before empty ranks in the year 2020 with competitions that took place with the usual audience in the previous two winter seasons at the very same locations. To address the second step, we partly followed the big data approach we proposed in Chapter 1.3 and were able to include 758 biathletes (in total: 57 251 shooting bouts including 286 255 shots) into analyses of competition data of the years 2005-2020.

Social Context: Impact of Audience on Skiing and Shooting Performance in Biathlon

Based on previous work on social facilitation effects (Allport, 1924; Zajonc, 1965) that highlighted the effect's task-specificity (Strauss, 2002), we examined audience effects for different task types that biathlon naturally comprises in an ecological valid high-performance setting. We assumed performance enhancements through the presence of an audience in the so-called *conditioning task* (i.e., skiing, see e.g. Worringham & Messick, 1983; Rhea et al., 2003; for an overview: Strauss, 2002) while previous work did not allow to draw final hypotheses for the *coordination task* (i.e., rifle shooting) with on the one hand evidence for performance decrements (e.g., Butki, 1994) and on the other hand for enhancements (e.g., Singer, 1965; Haas & Roberts, 1975).

Based on the present results, I first argue that social context is worth considering when explaining and predicting biathlon performance as both skiing and shooting performance were affected by the presence vs. absence of an audience. More specifically, our findings corroborated the task-specificity of these effects. Most interestingly and surprisingly, audience effects turned out to be additionally gender-specific: *Conditioning task* performance (i.e., cross-country skiing) was characterized by *social facilitation* in male biathletes (i.e., faster skiing times) in the presence compared to the absence of audience. However, while the inclusion of gender was not based on theoretical assumptions but for methodological reasons only (e.g., differing competition course, differing performance in both shooting and skiing), female athletes showed the opposite effect of social facilitation as they performed worse (i.e., skied slower) in presence vs. absence of audience. These unpredicted results become even more pronounced as the reverse pattern was observed on the *coordination task* of biathlon shooting: Male biathletes suffered from the presence of an audience in shooting times (i.e., longer shooting times) whereas females' performance was characterized by social facilitation effects (i.e., shorter shooting times) in the presence of an audience. This gender-specific pattern was also true for shooting accuracy in sprint competitions (featuring a bigger sample size than the second analyzed competition type of mass start) as males showed lower percentage hit rates with audience present compared to absent while females again showed *social facilitation* reflected in more accurate shooting in the presence of an audience. To sum up, male biathletes showed social facilitation effects predicted based on previous work (Strauss, 2002) while females showed a task-specific reverse pattern.

As systematic gender differences have not been a topic of social facilitation research, our first approach to explain the unexpected findings was to analyze previous work for a possible gender bias in sample characteristics (see Beery & Zucker, 2011; Cundiff, 2012; Correa-de-Araujo, 2006). In fact, a screening of Strauss (2002) comprehensive review revealed a clear selection bias towards male participants in motor performance related social facilitation research as two thirds (66 %) of the included participants were male but only 16 % were female (no information about gender distribution was provided for 18 % of the participants). Hence, past work meets the criteria of sample selection bias as it non-randomly excluded certain observations (in this case: female participants) that can threaten both internal and external validity of scientific work as results may not be generalizable (Heckman, 1979; Berk, 1983). Consequently, if our knowledge about social facilitation in motor tasks is for the most parts based on male participants, this selection bias might explain the unpredicted task-dependent opposite effects of an audience on elite male and female biathletes' performance.

Another attempt to explain the unpredicted findings is to look at them in the light of gender differences in related areas. On the one hand, it is conceivable that audience could trigger sex stereotype threat and gender roles (e.g., Hively & El-Alayli, 2014; for a review, see Chalabaev et al., 2013). As men are known to outperform women in conditioning tasks but not necessarily in coordination tasks (Chalabaev et al., 2013; see also Goldschmied & Kowalczyk, 2016), female biathletes may perform worse in cross country skiing when audience is present (out of fear to confirm a negative stereotype of women being inferior to men in this type of task), while males may increase their performance when being observed and evaluated. By contrast, a conceivable stereotype threat in biathlon shooting may enhance women's shooting performance but impair performance in men. On the other hand, gender differences in competitive attitudes (with males responding more positively and tending to improve their performance in competitions; e.g., Niederle & Vesterlund, 2011; Gneezy & Rustichini, 2004) may account for the observed results. As classic activation theories (Zajonc, 1965; Blascovich et al., 1999) reason benefits in simple (e.g., conditioning) tasks and performance losses in complex (e.g., coordination) tasks due to increased arousal and activation triggered by the audience might differ between men and women based on differences on competitive attitude, it is conceivable that males benefit in skiing but suffer in shooting while lower arousal in women results in performance decrements in skiing but enhancements in shooting.

Social Context: Impact of Co-Acting Competitors on Shooting Performance in Biathlon

In addition to the examination of audience effects in biathlon, the co-authors of Study 3 and I focused on the impact of co-acting competitors on shooting performance in elite biathletes (Chapter 4.2) by referring to social facilitation theory's pioneering study (Triplett, 1898). For operationalizing the presence of co-acting competitors, we analyzed on the one hand the impact of the number of co-acting biathletes at the shooting range and on the other hand the overlapping time with these competitors in head-to-head World Cup competitions (mass start and pursuit). To start with the former aspect, results indicate that a higher number of co-acting competitors predicts increased shooting accuracy which is in line with Triplett's (1898) observation of performance enhancements in the presence of co-acting athletes and the assumptions of social facilitation in general (Allport, 1924; Zajonc, 1965). This finding is especially noteworthy as social facilitation effects are seen to be task-specific (see Strauss, 2002; also discussed in Chapter 4.1) with equivocal findings in coordination tasks such as shooting. Consequently, the present findings corroborate previous work showing positive effects of other's presence not only in so-called conditioning but also in coordination tasks (e.g., Haas & Roberts, 1975; Dube & Tatz, 1991).

In contrast to shooting accuracy, social facilitation effects were not observed in shooting time. As accuracy contributes about ten times more to overall biathlon performance compared to shooting time (Luchsinger et al., 2019), it is conceivable that biathletes primarily focus on their shooting accuracy – an effect that is also mirrored in the impact of co-acting competitors on these performance measures.

In contrast to the number of present co-actors, we observed negative effects of higher overlapping time with co-acting biathletes on both shooting accuracy and shooting time. When referring to theoretical approaches to social facilitation theories (for an overview, see Chapter 4.1), these results can be interpreted by attentional exhaustion (Baron, 1986) caused by the longer time overlap with co-acting competitors. In addition, performance deteriorations in coordination tasks are explained by situations representing threat rather than challenge based on task complexity (Blascovich et al., 1999) or triggering interference of dominant responses (Zajonc, 1965). In this regard, one can only speculate that a longer presence of other biathletes may lead to these negative attentional processes and result in decreased shooting performance. Note though, that overlapping time is likely to be confounded with shooting time, thus, the association of longer overlapping time and longer shooting time has to be interpreted with caution.

Conclusion Regarding Biosocial Factors

To summarize, social context is worthy of integration in biathlon-specific research as the present findings revealed significant effects of the social context of an audience being present vs. being absent on both skiing and shooting performance. Additionally, our work provides first evidence for the impact of co-acting competitors on shooting performance.

However, social facilitation in terms of audience effects in biathlon seems to be both task- and gender-specific as male biathletes showed performance enhancements in the conditioning task (i.e., skiing) but decrements in the coordination task (i.e., shooting) when audience was present compared to absent while females' skiing performance was hampered in the presence of spectators but shooting performance benefited in audience conditions. One first attempt to explain the unpredicted gender-specificity might be a selection bias in previous work on social facilitation in motor tasks towards male participants (based on the analysis of a comprehensive review by Strauss, 2002). Furthermore, well-known gender differences such as stereotype threat or differences in competitive attitudes might underlie gender specificity.

The complexity of social facilitation effects in sports is also mirrored in the impact of co-acting competitors: While a higher number of co-acting biathletes were related to better shooting accuracy, thereby supporting social facilitation effects of co-actors (Triplett, 1898), shooting time was not affected. In contrast, more time overlap with co-acting competitors predicted both decreased shooting accuracy and longer shooting time.

While the present findings represent a starting point, they have to be validated to follow the fruitful route of gender differences in social facilitation research as well as for giving evidence-based recommendations for athletes and coaches. Consequently, future experimental research that allows us to systematically vary both task type and gender is needed to examine the exact processes underpinning those effects.

5.2 Methodological Considerations

The aim of understanding, explaining and predicting biathlon performance involves some methodological challenges and issues worth closer inspection. In this section, I discuss the most pertinent issues as well as present methodological approaches I applied to overcome them.

Recalling the central aim that includes not only the contribution to our scientific knowledge in biathlon but also the ability to transfer results into practice and to give evidence-based recommendations to athletes, coaches or sport psychologists, the consideration of representative design is of particular interest. The concept of representative design proposed by Egon Brunswick (Brunswick, 1956) describes the aim to use stimuli in an experimental setting that correspond to the organism's typical environment and is consequently representative for the situation the observed behavior is intended to be generalized. With regards to research in sport psychology, Pinder and colleagues (2011a) highlight the need of experimental task constraints that represent the constraints of the real sport performance environment the study is focusing on. Consequently, research examining high performance in one specific sport is well-advised to aim for information sources and athletes' responses that are comparable or even the same as in the real competitive environment (Araújo et al., 2007; Pinder et al., 2011b). In addition to these methodological key issues, Pluijms and colleagues (2013) highlight the role of generalizability as well as experimental control when aiming to present practical recommendations for athletes and coaches based on sport scientific research and knowledge:

First, Pluijms et al. (2013) outline the role of generalizability the study strives for. For instance, conclusions of experiments including expert athletes are seen to be generalizable to athletes with equivalent skill level but not for a broader population.

In addition, one must weigh between a possible lack of generalizability of experimental findings in laboratory settings to competitive settings and the advantage to simplify competitive situations and focus on one relevant aspect in laboratory experiments. The second aspect discusses the role of experimental control (Pluijms et al., 2013). In general, laboratory experiments compared to field studies provide a higher degree of control for eliminating, for instance, factors that may interfere with the effects but are not of interest (e.g., Lucas, 2003). However, participants might act differently in a laboratory setting (including e.g., simulated stimulus or task) compared to the field (i.e., in-situ; Dicks et al., 2010) – an aspect that becomes even more pronounced when aiming at predicting performance in athletes that are highly specialized in one specific sport, including specific situations, environment etc. (for a detailed discussion on representative design and ecological validity in sport psychological research, see also Araújo et al., 2007).

By taking these challenges seriously and addressing them appropriately, the research presented in this thesis took great efforts to provide biathletes with representative performance designs:

First and foremost, we aimed at creating a representative performance environment when developing the experimental setting of the first study. As the biopsychological approach involved physiological workload as well as shooting performance on the one hand and the role of gaze behavior on the other hand, representative task design, information sources and athletes' responses had to be comparable or even the same as in the real competition in both tasks. Consequently, the experimental setting consisted of four exercise bouts of roller skiing on a treadmill and four biathlon shooting blocks (including both prone and standing shooting) in an alternating manner and hence mimicked the structure of a biathlon competition (e.g., individual). Physiological demands of roller skiing are highly comparable to cross country skiing as it represents the same movement and is the most frequently used summer training tool in biathlon. Additionally, the use of a treadmill allowed to control physiological workload through the treadmill's speed and incline which speaks to the key issue of experimental control. Duration and intensity of the exercise bouts were based on lap times and physiological workload during a biathlon competition, respectively (e.g., Hoffman et al., 1992). The shooting task consisted of real biathlon shooting at an indoor shooting range covering 50 meters shooting distance on original biathlon targets using real ammunition. Finally, we carefully opted for physiological and especially psychological measurements (e.g., developed an Eye Tracking system for this purpose, see Chapter 2.3) that neither influenced the experimental procedure (e.g., through time delays based on, for instance, validating processes) nor interfered with the highly automatized shooting processes in expert biathletes.

In contrast to the biopsychological study (Chapter 3.1), the second and third empirical studies examining the role of social context for biathlon performance by building a biosocial bridge are based on analyses of archival competition data. This methodological approach on the one hand enabled us to address the research questions directly in the field and hence in athletes' real competitive environment but on the other hand ruled out experimental control.

In the present thesis, I was especially interested in biathlon performance in expert biathletes. As biathlon additionally represents a highly specialized area, generalizability is given for biathletes of a similar skill level but not for a broader population. Consequently, I aimed at examining biathletes with a high expertise level that is on the one hand mirrored in their membership in the German junior or senior national team (biopsychological study in Chapter 3.1) and achieved performance (e.g., shooting accuracy comparable to world class athletes, see also Luchsinger et al., 2018) and on the other hand in athletes' participation in World Cup events (biosocial studies presented in Chapter 4.1 and 4.2). Nevertheless, the co-authors and I examined expertise differences between elite and sub-elite athletes in the first study and additionally focused on the role of expertise that may influence the impact of social context (i.e., co-competitors' presence at the shooting range) on biathlon performance in the third study. This inclusion enabled us to identify reliable predictors between athletes of different expertise levels (e.g., elite biathletes showed faster shooting times but similar shooting accuracy compared to sub-elites) and consequently valuable implications for less skilled athletes. However, one consequence of conducting expertise research is the inherent issue of sample sizes as this research area is per definition dedicated to small sample sizes (McAbee, 2018) that may result in lowered statistical power. We were facing this methodological challenge by on the one hand analyzing competition data that allowed us to feature all international elite biathletes competing in World Cup events resulting in large sample sizes (especially in Study 3 when including 758 participants completing 57 251 shooting bouts). On the other hand, we aimed at a large sample in the experimental study (Study 1; Chapter 3.1) and were able to include 23 expert biathletes. However, the claim of an interdisciplinary approach was accompanied by a complex study design including a large variety of physiological, psychological and performance measurements, resulting in some technical issues that consequently allowed the inclusion of only subsets of participants for a few analyses (see Chapter 3.1.3). Consequently, we based our results not only on p-values but additionally discussed effect sizes. In addition, we interpreted our results cautiously.

Next to the generalizability to a broader population, generalizability is defined as the option to transfer results to another time and place. As we implemented a highly representative research design, conclusions should not be confined to particulars of time and place. Following Pluijms and colleagues (2013), one important aspect that one should consider when moving in the field of applied research is experimental control. In this regard, we aimed at high experimental control in the biopsychological study of the present thesis that included a focus on the relevant factors that should theoretically be tested (i.e., the impact of physiological workload on shooting performance, the role of gaze behavior) and ensured the exclusion of interfering effects such as wind or weather conditions at the shooting range. In contrast, as the biosocial studies did not follow an experimental approach, no experimental control about the analyzed competition data was given. Consequently, influencing factors that are not considered in the study cannot be ruled out. However, and in contrast to the experimental study, this methodological approach enabled us to feature a substantially larger sample size and observations so single influencing factors should not affect general results.

To sum up, the present thesis aimed at examining biathlon performance from different viewing angles of a biopsychosocial framework. To this end, we created a representative performance environment to test biopsychological factors in an experimental study that consequently allowed the generalizability to equally skilled biathletes in different settings and enabled a high degree of experimental control. Further, we examined the impact of social context on shooting and skiing performance by analyzing archival competition data and consequently tested our theoretical assumptions directly in the field that represents the real competitive environment. While the first approach benefits from high experimental control but goes hand in hand with constrained sample sizes, the second approach has its drawbacks in experimental control but enabled us to feature a big data set and to measure real behavior in real biathlon competitions.

5.3 Future Directions

The current work proposes a holistic, interdisciplinary approach to explain, predict and optimize performance in biathlon. Under the umbrella of the established biopsychosocial framework, the empirical studies contribute to our knowledge about expert performance in biathlon by questioning the impact of physiological workload as well as the role of gaze behavior for shooting performance (biopsychological approach) while also highlighting the need to focus on social context as this seems to affect both skiing and shooting performance in biathlon. Since the latter finding represents a novel viewing angle on biathlon performance, the current work represents a starting point for fruitful routes of future research.

Based on the findings of the biopsychological study that revealed an impact of physiological workload on shooting time but not on shooting accuracy and indicated shooting time as a reliable predictor for expertise level but did not corroborate the previous finding that specific gaze behavior (long final fixation) is related to better shooting accuracy, I ask for replication studies and the accumulation of data across multiple labs. This call is based on two reasons: First, previous work on the impact of physiological load on shooting performance not only showed inconsistent findings but also applied heterogeneous methods with respect to the experimental setting including, for instance, the examined tasks. Second, replication studies represent one way to address the inherent issue of small sample sizes in expertise research (Schapschröer et al., 2016) that also applies to experimental research in biathlon experts. As elite biathletes represent a very exclusive sample and most laboratories gain, if ever, access to the national teams of the countries they are located in, working together across labs by applying the same methodological approaches would enable us to reach higher samples, increase statistical power of our studies and consequently prove the robustness of present findings in biathlon research. This call for replications also includes the further examination of the role of gaze behavior in biathlon as the present study is questioning previous results of Vickers and Williams

(2007) that again applied different methods and measurements. Furthermore, results indicate large individual differences regarding the final fixation durations with accurate shooting performance being maintained (Chapter 3.1.3 & Chapter 3.1.4). As individually different fixation behavior seems to be related to successful biathlon shooting, future research would be well-advised to focus on inter-individual but also intra-individual differences of fixation duration (for a discussion of individual differences in performance and motor skill learning, see Anderson et al., 2021).

With the aim of providing evidence-based recommendations for processes of talent development and guidelines for training in biathlon, research including more levels of expertise is needed. Since the first study revealed crucial performance differences in shooting time but not in accuracy depending on expertise level, including a higher range of expertise would enable us to identify more predictors that change with higher expertise. Consequently, coaches and athletes could be advised to focus on specific factors determining performance at specific stages of their athletic development (e.g., youth, junior and senior athletes). However, this would not only be a promising future pathway with regards to the first study but also for biosocial research in biathlon. Future research might look at the robustness of both task- and gender-specific audience effects and social facilitation effects evoked by co-acting competitors in athletes featuring a lower expertise level. To do so, archival competition data of the competition series below World Cup, that is *IBU-Cup* and *IBU-Junior-Cup* would provide the opportunity to examine especially the latter effect as the study on audience effects is based on the COVID-19 restrictions that represent a unique setting.

While the current thesis does not follow a fundamental research perspective but pursued sport-specific research with the aim of transferring theoretical findings into practice, the surprising findings of task-specific gender differences in social facilitation effects (see Chapter 4.1) that are not predicted in literature call for a fundamental research perspective to validate these results. In this regard, a systematic investigation of gender differences in an experimental set-up including the variation of tasks is needed. This approach would allow us – in contrast to the present study – to examine the psychological processes driving these effects. Moreover, as outlined in Chapter 4.1.6, the current sample size was naturally limited, and experimental research could include a bigger sample and consequently achieve higher statistical power. Next to explicitly addressing gender differences in social facilitation, the present finding of sample selection bias in previous research on social facilitation in motor tasks calls for balanced gender distribution in future research.

Finally, the present research has begun to build interdisciplinary bridges and provides initial steps to apply a more holistic approach when examining performance factors in elite sports. However, the final step when aiming at understanding, explaining, and predicting biathlon performance that is the inclusion of all viewing angles of the established biopsychosocial framework in a big data approach (see Chapter 1.3.8) still needs to be taken. Big data approaches are not only characterized by featuring a high data volume but also by diverse data sets and the aim of capturing the entire population one is interested in (Kitchin, 2014). Consequently, this approach would enable us to focus on biological factors both based on training and competition (i.e., physiological or biomechanical measurements of skiing and shooting performance), on psychological aspects including personality characteristics, but also psychological states or attentional processes and on social context information. Finally, these multi-methodologically gathered data (e.g., physiological monitoring, biomechanical measurements, self-reports) could be connected with performance data to get a deeper understanding of what exactly characterizes an Olympic champion and which factors differentiate between reaching the podium or not. As already mentioned in Chapter 1.3.8, a big data approach and hence the final step in building interdisciplinary bridges requires collaborations across disciplines in sport scientific research and between practitioners such as athletes, coaches or sport psychologists and scientists. Nevertheless, a big data approach would bring us closer to our aim of understanding, explaining, predicting and consequently optimizing biathlon performance in an interdisciplinary and holistic manner.

Recapitulating the quote by the US-biathlete Clare Egan in the introduction who highlighted the role of co-competitors hitting all targets as well as screaming fans and contrasted this situation with the apparently simple task of repeating what she has done thousands of times, biathlon-specific research corroborates that biathlon performance is affected by a wide range of biological, psychological and social aspects. This thesis aimed at contributing to the current understanding of performance in biathlon, established a biopsychosocial framework and consequently took first steps to build interdisciplinary bridges by addressing the impact of physiological workload on shooting performance and the role of gaze behavior therein as well as by examining the role of social context such as the presence of an audience and co-acting competitors. The presented results constitute starting points for future research to understand, explain, predict and consequently optimize biathlon performance, including big data approaches.

6 References

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7 Zusammenfassung der Dissertationsschrift (deutsch)

Einleitung

> *“Race across the snow on skis as fast as you can. Now stop and shoot a target the size of an Oreo about 54 yards away. If you miss, you’ll ski penalty laps before you are allowed to race to the next set of targets.” (Parker-Pope, 2018).*

Dieses Zitat der US-Biathletin Clare Egan veranschaulicht die olympische Sportart Biathlon auf eine lebendige Art und Weise. Wie in dem Zitat dargestellt, vereint Biathlon zwei sehr unterschiedliche Aufgaben in einer Sportart: Skilanglauf in der freien Technik und Schießen mit einem Kleinkalibergewehr. Um in dieser Sportart erfolgreich zu sein, müssen Biathlet*innen somit nicht nur schnell laufen, sondern auch unter hoher physiologischer Belastung präzise und schnell schießen. Auf Grundlage dieser Anforderungen erscheint es nachvollziehbar, dass die Sportart Biathlon hohe physiologische, aber auch psychologische Anforderungen an Athlet*innen stellt.

Aus der Perspektive der angewandten Sportwissenschaft verfolgt Forschung im Biathlon das Ziel, Sportler*innen, Trainer*innen, aber beispielweise auch Sportpsycholog*innen evidenzbasierte Hinweise und Empfehlungen für ihre Arbeit in der Sportart zu geben. Mit Blick auf die Grundlagenforschung hingegen bietet Biathlon die Möglichkeit, Einblicke in das Zusammenspiel von physiologischer Belastung und feinmotorischer Kontrolle zu erlangen und unser Wissen bezüglich biologischer, psychologischer und sozialer Leistungsfaktoren in einer Umgebung hoher sportlicher Expertise zu erweitern. Wie ein aktuelles Review von Laaksonen und Kollegen (2018) hervorhebt, wurde ebendiese interdisziplinäre Verknüpfung verschiedener Leistungsfaktoren in der bisherigen Forschung in der Sportart Biathlon jedoch vernachlässigt. Stattdessen wurden insbesondere physiologische und biomechanische sowie psychologische Determinanten isoliert untersucht – ein Ansatz, der der Komplexität von Spitzenleistungen im Biathlon nicht gerecht wird.

Das Ziel der vorliegenden Dissertation war es somit, mit einen ganzheitlichen und interdisziplinären Ansatz dazu beizutragen, Biathlonleistung zu verstehen, zu erklären und vorherzusagen, um sie in der Folge optimieren zu können. Zu diesem Zweck wird zunächst ein theoretischer Rahmen in Form eines biopsychosozialen Modells entwickelt. Auf Grundlage dieses Rahmenwerkes werden die Forschungsfragen der vorliegenden Promotion vorgestellt sowie methodische Überlegungen dazu geteilt. Den Hauptteil des Promotionsprojektes bilden drei interdisziplinäre Studien, die in der Folge kurz zusammengefasst werden. Eine theoretische Diskussion und Zusammenfassung der Studien bilden den Abschluss der deutschsprachigen Zusammenfassung.

Ein biopsychosoziales Modell als Wegweiser für interdisziplinäre Forschung im Biathlon

<u>Basierend auf folgender Publikation:</u>

Heinrich, A., Stoll, O. & Cañal-Bruland, R. (2021). A biopsychosocial framework to guide research on biathlon performance. *Frontiers in Psychology, 12,* 671901. https://doi.org/10.3389/fpsyg.2021.671901

In den letzten Jahrzehnten hat eine wachsende Anzahl wissenschaftlicher Publikationen zu unserem Wissen beigetragen, welche Faktoren Leistung in der Sportart Biathlon determinieren (siehe Review von Laaksonen et al., 2018). Die Forschung bezog sich dabei vor allem auf biologische (d.h., physiologische oder biomechanische) Parameter sowie auf psychologische Aspekte von Biathlonleistung. Soziale Einflussfaktoren hingegen wurden bis auf eine Ausnahme (Harb-Wu & Krumer, 2019) weitgehend übergangen.

Biologische Leistungsfaktoren. Im Hinblick auf biologische Faktoren stellte die bisherige biathlonspezifische Forschung heraus, dass Biathlet*innen mit einer höheren Sauerstoffaufnahmekapazität bessere Laufleistungen zeigen (Rundell & Bacharach, 1995; Rundell, 1995; Laaksonen et al., 2020), die durch die höhere physiologische Belastung, die mit dem Tragen der Waffe einhergeht, noch an Bedeutung gewinnt (Frederick, 1987; Rundell & Szmedra, 1998; Jonsson Kårström et al., 2019; Stoeggl et al., 2015; Jonsson Kårström et al., 2019). Neben diesen physiologischen Parametern wird Leistung im Biathlon weiter durch biomechanische Aspekte bestimmt, die ebenfalls zu biologischen Leistungsfaktoren zählen: Erfolgreiche Biathlet*innen lassen sich auf Grundlage einer höheren Waffenstabilität (Sattlecker et al., 2014; Hoffman et al., 1992; Sattlecker et al., 2017), stabileren Zielmustern sowie höherer posturaler Kontrolle (Sattlecker et al., 2014; Sattlecker et al., 2017; Groslambert et al., 1999) von weniger erfolgreichen Biathlet*innen unterscheiden. Darüber hinaus wird ein höherer Schulterdruck auf die Waffe ebenso wie ein spezifisches Abzugsverhalten (ansteigender Druck gefolgt von einem Druckplateau; Sattlecker et al., 2017; Hansen et al., 2019) mit höherer Schießleistung in Verbindung gebracht. Einige Studien beschäftigten sich schließlich mit dem Einfluss von physiologischer Belastung auf die Schießleistung, wobei die Ergebnisse keine eindeutigen Schlussfolgerungen zulassen: Während einige Untersuchungen Einbußen in der Trefferleistung durch erhöhte physiologische Belastung zeigten (Hoffman et al., 1992; Grebot et al., 2003; Vickers & Williams, 2007; Ihalainen et al., 2018), konnten andere Studien keine Effekte nachweisen (Gallicchio et al., 2016; Luchsinger et al., 2016).

Psychologische Leistungsfaktoren. Psychologische Forschung im Biathlon untersuchte bisher psychologische Prozesse (u.a., neurophysiologische Mechanismen), die insbesondere der Schießleistung zugrunde liegen sowie die Wirksamkeit psychologischer Interventionen. In diesem Zusammenhang zeigten Studien, dass erfolgreiches Biathlonschießen mit höherer frontalen *Theta Power* in Verbindung gebracht wird, die für eine erhöhte fokussierte Aufmerksamkeit steht (Gallicchio et al., 2016; Luchsinger et al., 2016). Die Bedeutung dieser Aufmerksamkeitsprozesse wurde von einer Untersuchung von Vickers und Williams (2007) weiter gestützt, die spezifisches Blickverhalten mit höherer Trefferleistung assoziierten (je länger die finale Fixation vor Schussabgabe, desto höher die Trefferleistung). Darüber hinaus zeigte Lindner (2017) basierend auf archivierten Wettkampfdaten, dass die Wahrscheinlichkeit, den letzten Schuss des finalen Schießens zu verfehlen, insbesondere bei den führenden Sportler*innen eines Biathlonwettkampfes signifikant höher ist als ein Fehler bei den vier vorhergehenden Schüssen. Dieses Ergebnis bringt der Autor mit dem psychologischen Druck, der bei diesem letzten Schuss herrscht, in Verbindung. Psychologische Interventionen wie autogenes Training, Vorstellungs- oder Entspannungstraining schließlich haben das Potential, in Kombination mit Schießtraining die Trefferleistung (Laaksonen et al., 2011) und Waffenstabilität (Groslambert et al., 2003) zu erhöhen.

Soziale Leistungsfaktoren. Im Gegensatz zu biologischen und psychologischen Leistungsfaktoren hat die Forschung soziale Aspekte im Biathlon bisher weitgehend übergangen und unser Wissen über den Einfluss des sozialen Kontexts ist dementsprechend stark limitiert. Die einzige Ausnahme bildet eine Studie von Harb-Wu und Krumer (2019), die basierend auf Wettkampfdaten sowohl Schieß- als auch Laufleistungen von Elitebiathlet*innen bei Wettkämpfen im Ausland (nicht unterstützendes Publikum) mit Wettkämpfen vor heimischen Zuschauern (unterstützendes Publikum) verglich. Die Ergebnisse untermauern die Bedeutung von sozialem Kontext für die Biathlonleistung: Während Sportler*innen mit dem höchsten Leistungsniveau vor unterstützendem Publikum signifikant mehr Scheiben verfehlten, zeigten Biathlet*innen mit grundsätzlich geringerem Leistungsniveau keine Leistungseinbußen im Schießen, sondern steigerten ihre Laufzeiten (d.h., liefen vor heimischen Publikum schneller).

Zusammengefasst lässt sich festhalten, dass biathlonspezifische Forschung in der Vergangenheit zum einen vor allem biologische (d.h., physiologische und biomechanische) und psychologische Leitungsaspekte untersuchte, wohingegen der Einfluss des sozialen Kontextes weitgehend übergangen wurde. Zum anderen wurden diese Faktoren meist isoliert statt in Verbindung betrachtet, obwohl sie im Biathlonwettkampf stets in Verbindung auftreten. Aus diesem Grund wird ein ganzheitlicher, interdisziplinärer Ansatz in Form eines biopsychosozialen Rahmens vorgeschlagen, um unser Verständnis, welche Faktoren Leistung im Biathlon beeinflussen, zu erweitern und zukünftige Forschung zu leiten.

Forschungsfragen und methodische Überlegungen

Basierend auf der dargestellten Forschungslücke, die zum einen die isolierte Betrachtung biologischer und psychologischer Leistungsfaktoren im Biathlon und zum anderen die fehlende Berücksichtigung sozialer Aspekte betrifft, verfolgt das vorliegende Dissertationsprojekt zwei Hauptziele:

Das erste Ziel stellt einen Beitrag zu unserem Verständnis von Biathlonleistung mit Hilfe eines interdisziplinären Forschungsansatzes dar. Da biopsychologische Forschung im Biathlon bisher rar ist und eine große Heterogenität sowohl bezüglich der Studienergebnisse als auch der angewandten Methoden aufweist, verbindet die erste empirische Studie biologische und psychologische Aspekte biathlonspezifischer Leistung und untersucht den Einfluss physiologischer Belastung auf die Schießleistung sowie die Rolle von Blickverhalten in diesem Zusammenhang. Dabei wird die einzige Studie, die in der Vergangenheit Blickverhalten im Biathlon untersucht wird (Vickers & Williams, 2007) unter Bedingungen hoher ökologischer Validität konzeptuell repliziert.

Im Rahmen des zweiten Ziels wird die Forschungslücke im Bereich der sozialen Aspekte adressiert, indem wiederum ein interdisziplinären Ansatz gewählt und sowohl biologische als auch soziale Faktoren mit einbezogen werden. So untersucht die zweite empirische Studie den Einfluss des sozialen Kontextes in Form von Anwesenheit vs. Abwesenheit von Publikum, während Studie 3 die Rolle von co-agierenden Konkurrent*innen am Schießstand in den Fokus nimmt.

Dem empirischen Teil des Dissertationsprojektes liegen methodische Überlegungen zugrunde, die im Folgenden kurz dargestellt werden:

Erstens bedingt das Ziel, zu unserem Wissen und Verständnis von Biathlonleistung auf einem Hochleistungslevel beizutragen, den Einbezug von Teilnehmer*innen mit einem hohen Expertiseniveau in der Sportart Biathlon. Diesem Aspekt wird in der ersten Studie durch die Untersuchung von der deutschen Biathlonnationalmannschaft sowie der Juniorennationalmannschaft Rechnung getragen. In der zweiten und dritten Studie werden archivierte Wettkampfdaten von Biathlon Weltcuprennen analysiert, sodass insbesondere in Studie 3 alle internationalen Weltklasseathleten der Jahre 2005 bis 2020 in die Untersuchungen miteingeschlossen werden können (Big Data Analyse).

Darüber hinaus ist es das Ziel, die biopsychologischen und biosozialen Leistungsfaktoren unter Bedingungen hoher ökologischer Validität zu erforschen. Basierend auf diesem Ziel werden beide Aufgaben der Sportart Biathlon (Skilanglauf in der freien Technik und Schießen mit einem Kleinkalibergewehr) in die erste Untersuchung mit eingeschlossen. Im Gegensatz zu einer Vielzahl früherer Studien liegt der Fokus zudem nicht nur auf Trefferleistung, sondern auch auf der zweiten Leistungsdeterminante, der Schießzeit, und es werden beide Schießpositionen berücksichtigt (liegender Anschlag und stehender Anschlag). Darüber hinaus wird in Studie 1 tatsächliches Biathlonschießen unter Verwendung von Munition anstelle von einer simulierten Schießaufgabe durchgeführt und, ebenfalls im Gegensatz zu einigen früheren Studien, physiologische Belastung nicht durch ein Radergometer, sondern durch Skiroller-Lauf auf einem speziellen Laufband induziert, das die gleichen Anforderungen wie Skilanglauf bei höherer Kontrollierbarkeit der Belastungssteuerung mit sich bringt.

Während in Studie 2 und 3 archivierte Wettkampdaten analysiert werden, die die größtmögliche ökologische Validität aufweisen, indem sie reales Verhalten in realen Wettkämpfen abbilden, resultiert der Anspruch hoher ökologischer Validität sowie der interdisziplinäre Forschungsansatz in der ersten Studie in einem komplexen Studiendesign, da verschiedene physiologische Daten, detaillierte Schießleistungsdaten sowie Blickverhaltensdaten erfasst wurden. Für die spezifischen Anforderungen des Biathlonschießens wurde in Vorbereitung der Studie ein Eye Tracking System entwickelt. Detaillierte Informationen sind folgender Veröffentlichung zu entnehmen:

Proceedings Paper:

Hansen, D. W., Heinrich, A. & Cañal-Bruland, R. (2019). Aiming for the quiet eye in biathlon. In *Proceedings of the Symposium on Eye Tracking Research and Applications* (ETRA '19; article No. 10;*1-7*). ACM, New York, NY, USA.
https://doi.org/10.1145/3314111.3319850

Der Einfluss von physiologischer Ermüdung und Blickverhalten auf die Schießleistung von erfahrenen Biathlet*innen

Studie 1, basierend auf folgender Publikation:

Heinrich, A., Hansen, D. W., Stoll, O. & Cañal-Bruland, R. (2020). The impact of physiological fatigue and gaze behavior on shooting performance in expert biathletes. *Journal of Science and Medicine in Sport, 23*(9*),* 883-890.
https://doi.org/10.1016/j.jsams.2020.02.010

Ziel der Studie. Die olympische Sportart Biathlon kombiniert Skilanglauf in der freien Technik mit Kleinkalibergewehrschießen und erfordert somit hohe Trefferleistungen und schnelle Schießzeiten unter enormer physiologischer Belastung. Aufbauend auf eine Studie von Vickers und Williams (2007) untersucht die vorliegende Studie den Einfluss von physiologischer Belastung und Blickverhalten auf die

Schießleistung (Trefferleistung und Schießzeit) von Elite und Sub-Elitebiathlet*innen.

Design und Methodik. Zehn Mitglieder der deutschen Biathlonnationalmannschaft (Elite) und 13 Mitglieder der deutschen Biathlonjuniorennationalmannschaft (Sub-Elite) nahmen an einem Leistungstest teil. Dabei absolvierten die Athlet*innen einen Skiroller-Test auf einem Laufband, der aus vier Stufen mit jeweils steigender Intensität bestand. Zwischen den Stufen wurde eine Schießeinlage mit jeweils fünf Schüssen in liegender bzw. stehender Position absolviert. Dabei wurde an einem Indoor-Schießstand aus einer Distanz von 50 Meter auf originale Biathlonscheiben geschossen (liegend: 4.5 cm Durchmesser; stehend: 11.5 cm Durchmesser).

Es wurden physiologische Parameter, bestehend aus Herzfrequenz und Laktatmessung, sowie Schießleistungsdaten, bestehend aus Trefferleistung und Schießzeit, erfasst. Darüber hinaus wurde das Blickverhalten der Sportler*innen, d.h. die Dauer der finalen Fixation mithilfe eines an der Waffe montierten Eye Tracking Systems aufgenommen.

Ergebnisse. Der Manipulationscheck zeigte einen systematischen Anstieg der physiologischen Belastung über die Stufen des Leistungstests hinweg. Elitebiathlet*innen benötigten signifikant kürzere Schießzeiten als Sub-Elitebiathlet*innen, während sie sich in der gezeigten Trefferleistung nicht unterschieden. Beide Gruppen zeigten längere Schießzeiten mit steigender physiologischer Belastung, wohingegen keine Effekte auf die Trefferleistung festzustellen waren. Die Analyse eines Subsets der Daten schließlich zeigte keinen Zusammenhang zwischen der Dauer der finalen Fixation und Trefferleistung.

Zusammenfassung. Physiologische Ermüdung scheint keinen Einfluss auf die Trefferleistung von Elite-Biathlet*innen zu nehmen, die Schießzeiten jedoch negativ zu beeinflussen. Darüber hinaus scheint die Dauer der finalen Fixation Trefferleistung von Elite- und Sub-Elitebiathlet*innen nicht zu moderieren, wobei diese Ergebnisse im Gegensatz zu früheren Ergebnissen stehen (Vickers & Williams, 2007).

Selektionsverzerrung in der Social Facilitation Theorie? Zuschauereffekte auf die Leistung von Elite-Biathlet*innen sind geschlechtsspezifisch

<u>Studie 2, basierend auf folgender Publikation:</u>

Heinrich, A., Müller, F., Stoll, O. & Cañal-Bruland, R. (2021). Selection bias in social facilitation theory? Audience effects on elite biathletes' performance are gender-specific. *Psychology of Sport and Exercise, 55*, 101943. https://doi.org/10.1016/j.psychsport.2021.101943

Ziel der Studie. Die *social facilitation* Theorie (Allport, 1924; Zajonc, 1965) geht von Veränderungen in der gezeigten kognitiven oder physischen Leistung – grundsätzlich in positiver Richtung – durch die Anwesenheit anderer (z.B. Publikum) aus. Während diese Theorie bezüglich konditioneller Aufgaben (z.B. Laufen, Gewichtheben) als robust gilt, sind die Studienergebnisse bezüglich des Einflusses anderer auf Leistung in koordinativen Aufgaben (z.B. Gleichgewichts- oder Präzisionsaufgaben) heterogen (Strauss, 2002). Die Sportart Biathlon vereint mit der Kombination Skilanglauf und Kleinkalibergewehrschießen beide Aufgabentypen und stellt somit ein einmaliges Setting dar, um die Aufgabenspezifik der *social facilitation* Theorie im Spitzensport zu überprüfen.

Design und Methodik. Das Verbot von Publikum im Biathlon Weltcup aufgrund der COVID-19 Pandemie bedingte einen Vergleich der Langlauf- und Schießleistungen in Abwesenheit von Zuschauern (März 2020) mit den äquivalenten Wettkämpfen, die in der vorausgegangenen Saison (2018/19) vor Publikum ausgetragen wurden. In diesem Zusammenhang wurden die archivierten Wettkampfdaten von vier Sprint- (83 Biathlet*innen) und zwei Massenstartwettkämpfen (34 Biathlet*innen) analysiert. Aufgrund geschlechtsspezifischer Leistungsunterschiede sowie unterschiedlicher Wettkampfregularien wurde der Faktor Geschlecht in die Analysen mit aufgenommen.

Ergebnisse. Die Ergebnisse untermauern die Aufgabenspezifik von Publikumseffekten, die jedoch zudem vom Geschlecht abhängen. So zeigen Männer in Anwesenheit von Publikum Leistungssteigerungen bei der konditionellen Aufgabe (d.h., schneller Laufzeiten) und Leistungseinbußen bei der koordinativen Aufgabe (längere Schießzeiten und geringere Trefferleistung). Die Ergebnisse der Frauen hingegen weisen ein genau umgekehrtes Muster auf, da sie vor Zuschauern langsamer laufen, jedoch genauer und schneller Schießen als in Abwesenheit von Zuschauern.

Zusammenfassung. Die Abhängigkeit des Publikumseffektes vom Geschlecht wird in der Literatur bisher nicht vorhergesagt, was durch eine selektive Stichprobenverzerrung früherer Untersuchungen zugunsten männlicher Teilnehmer (< 1/3 Frauen) bedingt sein könnte. Die vorliegenden Ergebnisse stellen somit die Generalisierbarkeit der *social facilitation* Theorie in Frage und dient als Ausgangspunkt für die systematische Untersuchung aufgabenspezifischer Geschlechtsunterschiede.

Der Einfluss von co-agierenden Konkurrent*innen auf die Schießleistung bei Elite-Biathlet*innen

<u>Studie 3, basierend auf folgendem, zur Begutachtung eingereichten Manuskript:</u>
Heinrich, A., Köhler, H., Müller, F., Stoll, O. & Cañal-Bruland, R. (submitted). The impact of co-acting competitors on shooting performance in elite biathletes.

Ziel der Studie. Ausgehend von der *social facilitation* Theorie (Allport, 1924), die von Leistungssteigerungen durch die Anwesenheit anderer bei kognitiven oder motorischen Aufgaben ausgeht, untersuchte die vorliegende Studie den Einfluss co-agierender Konkurrenten auf die Schießleistung im Elite-Biathlon. Zu diesem Zweck wurde basierend auf Wettkampfdaten sowohl der Einfluss der Anzahl anwesender Konkurrenten als auch die Überlappungszeit zwischen co-agierenden Biathlet*innen auf die Schießzeit und die Trefferleistung untersucht.

Design und Methodik. Es wurden archivierte Wettkampfdaten von Biathlon Weltcuprennen der Jahre 2005 bis 2020 analysiert. Diese beinhalteten 115 Massenstart- und 195 Verfolgungswettkämpfe von insgesamt 758 Elitebiathlet*innen, die 57.251 Schießblöcke und somit 286.255 Einzelschüsse absolvierten. Aufgrund der hierarchischen Datenstruktur wurden die Daten mit einem Multilevel-Ansatz ausgewertet.

Ergebnisse. Es lassen sich zwei Hauptergebnisse festhalten: Zum einen zeigten die Athlet*innen höhere Trefferleistungen, je mehr Konkurrenten ebenfalls am Schießstand schossen. Auf die Schießzeit hingegen hatte die Anzahl der co-agierenden Biathlet*innen keinen Einfluss. Zum anderen beeinflusste eine längere Überlappungszeit am Schießstand sowohl Schießzeit als auch Trefferleistung negativ (längere Schießzeiten und niedrigere Trefferleistungen).

Zusammenfassung. Die vorliegende Studie liefert erste Hinweise darauf, dass co-agierende Konkurrent*innen — sowohl in Bezug auf die Anzahl der Konkurrent*innen als auch auf die Überlappungszeit beim Schießen — die Schießleistung von Elite-Biathlet*innen beeinflusst.

Theoretische Diskussion und Zusammenfassung

Das zentrale Ziel der vorliegenden Dissertation lag zum einen in der gemeinsamen Betrachtung biologischer und psychologischer Faktoren, um Biathlonleistung besser zu verstehen und vorhersagen zu können. In diesem Zusammenhang wurde der Einfluss physiologischer Belastung sowie die Rolle spezifischen Blickverhaltens auf die Schießleistung im Biathlon untersucht, wobei methodische Limitationen der konzeptuell replizierten Studie (Vickers & Williams, 2007) adressiert wurden.

Zum anderen lag der Fokus auf der Untersuchung sozialer Einflussfaktoren (Publikum und co-agierende Konkurrent*innen), die in der bisherigen biathlonspezifischen Forschung nicht berücksichtigt wurden. Im Rahmen des zweiten Ziels wurde wiederum ein interdisziplinärer Ansatz gewählt und sowohl biologische als auch soziale Faktoren mit einbezogen. So untersucht die zweite empirische Studie den Einfluss des sozialen Kontextes in Form von Anwesenheit vs. Abwesenheit von Publikum, während Studie 3 die Rolle von co-agierenden Konkurrenten am Schießstand in den Fokus nimmt.

Psychobiologische Brücken bauen: Der Einfluss physiologischer Belastung auf die Schießleistung und die Rolle des Blickverhaltens für erfolgreiches Biathlonschießen

Die vorliegende Arbeit bietet neue Einblicke in den komplexen Zusammenhang zwischen physiologischer Belastung, Blickverhalten und Schießleistung, indem sie interdisziplinäre Brücken schlägt und einen biopsychologischen Ansatz anwendet. In erster Linie deuten die Ergebnisse darauf hin, dass erfahrene Biathlet*innen in der Lage sind, auch unter enormer physiologischer Belastung eine hohe Trefferleistung aufrechtzuerhalten, wohingegen die Schießzeit durch steigende Belastung negativ beeinflusst wird. Darüber hinaus erwies sich die Schusszeit, nicht aber die Trefferleistung, als zuverlässiger Faktor zur Vorhersage des Expertiseniveaus der Sportler*innen. Schließlich und im Gegensatz zu früheren Arbeiten (Vickers & Williams, 2007) schien die Dauer der endgültigen Fixierung für ein erfolgreiches Biathlonschießen nicht relevant zu sein und wurde — ähnlich wie die Trefferleistung — nicht durch zunehmende physiologische Ermüdung beeinflusst.

Biosoziale Brücken bauen: Der Einfluss der Anwesenheit anderer auf Lauf- und Schießleistung im Biathlon

Auf Grundlage der vorliegenden Studienergebnisse, die sowohl signifikante Effekte eines anwesenden bzw. abwesenden Publikums auf die Lauf- und Schießleistung als auch den Einfluss von co-agierenden Konkurrent*innen auf die Leistung am Schießstand zeigen, erscheint es sinnvoll, den sozialen Kontext in die biathlonspezifische Forschung einzubeziehen.

Die im Hinblick auf das Publikum beobachteten social facilitation Effekte im Biathlon scheinen jedoch sowohl aufgaben- als auch geschlechtsspezifisch zu sein, da männliche Biathleten Leistungssteigerungen in der Konditionsaufgabe (d.h., Skilanglauf), jedoch Leistungseinbußen in der Koordinationsaufgabe (d.h., Schießen) zeigten, wenn das Publikum anwesend (vs. abwesend) war, während die Laufleistung der Frauen in Anwesenheit von Zuschauern beeinträchtigt wurde, aber die Schießleistung von den Zuschauern profitierte. Ein erster Erklärungsversuch für die nicht vorhergesagte Geschlechtsabhängigkeit könnten verzerrte bzw. selektive Stichproben in früheren Studien zu social facilitation bei motorischen Aufgaben zugunsten männlicher Teilnehmer sein (basierend auf der Analyse eines umfassenden Reviews von Strauss, 2002). Darüber hinaus könnten bekannte Geschlechtsunterschiede wie wahrgenommene Bedrohung durch Stereotypen oder Unterschiede in der Einstellung gegenüber Wettkämpfen dem beobachteten Effekt zugrunde liegen. Die vorliegenden Befunde stellen einen Ausgangspunkt für zukünftige experimentelle Untersuchungen dar, die es erlauben, sowohl den Aufgabentyp als auch das Geschlecht systematisch zu variieren, um die Effekte zu validieren und die genauen Prozesse zu untersuchen, die diesen Effekten zugrunde liegen.

Neben den beobachteten Publikumseffekten zeigte die zweite Studie den Einfluss co-agierender Konkurrent*innen auf die Schießleistung am Schießstand. Auf der einen Seite ging eine höhere Anzahl co-agierender Konkurrent*innen mit höherer Trefferleistung einher und unterstütze so die Annahme von social facilitation Effekten in Verbindung mit anwesenden Konkurrent*innen (Triplett, 1898). Bezüglich der Schießzeit konnten an dieser Stelle jedoch keine Effekte beobachtet werden. Auf der anderen Seite sagten längere Überlappungszeiten mit den co-agierenden Konkurrent*innen schlechtere Schießleistungen in Form von geringerer Trefferleistung und langsameren Schießzeiten voraus. Grundsätzlich werden Leistungseinbußen bei Koordinationsaufgaben in Anwesenheit anderer (siehe Strauss, 2002) mit Erschöpfungserscheinungen im Bereich der Aufmerksamkeit (Baron, 1986) oder der Wahrnehmung einer Situation als Bedrohung (Blascovich et al., 1999) in Verbindung gebracht. Bezogen auf die vorliegenden Ergebnisse wäre es denkbar, dass eine längere zeitliche Überlappung mit co-agierenden Konkurrent*innen diese Aufmerksamkeitsprozesse auslöst und folglich zu einer geringeren Trefferleistung führt. Im Gegensatz zur zeitlichen Überlappung könnte man spekulieren, dass eine höhere Anzahl von anwesenden Konkurrent*innen eine ausschließliche Fokussierung auf relevante Reize (siehe Overload-Hypothese; Baron, 1986) und damit eine Leistungssteigerung zur Folge haben könnte.

Ausblick

Die vorliegende Dissertation bietet zahlreiche Anhaltspunkte für zukünftige Forschung: Im Hinblick auf die erste Studie werden Replikationsstudien als sinnvoll erachtet, um die inkonsistenten Befunde sowie die heterogenen Methoden vorheriger Studien zum Einfluss physiologischer Belastung auf die Schießleistung im Biathlon zu adressieren und Daten über mehrere Labore hinweg zu akkumulieren. Dieser Ansatz würde zudem dem inhärenten Problem kleiner Stichproben in der Expertiseforschung und somit geringer statistischer Power begegnen (Schapschröer et al., 2016). Die Forderung nach Replikationen schließt auch die weitere Untersuchung der Rolle des Blickverhaltens im Biathlon ein, da die vorliegende Studie frühere Ergebnisse von Vickers und Williams (2007) in Frage stellt, die wiederum andere Methoden verwendeten.

Mit dem Ziel, evidenzbasierte Empfehlungen für Prozesse der Talententwicklung und Richtlinien für das Training im Biathlon zu geben, wäre zukünftige Forschung außerdem gut beraten, mehrere Leistungsniveaus mit einzubeziehen. Auf diese Weise wäre es möglich, weitere Prädiktoren zu identifizieren, die sich mit steigender Expertise verändern.

Die überraschenden und in der Literatur nicht vorhergesagten Befunde zu aufgaben- und geschlechtsspezifischen Publikumseffekten machen Grundlagenforschung zur Validierung dieser Ergebnisse notwendig. Dieser Ansatz würde es — im Gegensatz zur vorliegenden Studie — erlauben, die psychologischen Prozesse zu untersuchen, die diese Effekte antreiben. Neben der expliziten Berücksichtigung von Geschlechtsunterschieden in Forschung zu social facilitation scheint eine ausgewogene Geschlechterverteilung in zukünftigen Studien bedeutend, um Verzerrungen der Stichprobenauswahl zukünftig zu vermeiden.

Die vorliegende Arbeit hat begonnen, interdisziplinäre Brücken in der Biathlonforschung zu bauen und erste Schritte in Richtung eines ganzheitlicheren Ansatzes bei der Untersuchung von Leistungsfaktoren im Spitzensport zu gehen.

Der nächste Schritt zur Erklärung und Vorhersage von Biathlonleistungen, nämlich die Einbeziehung aller Perspektiven des dargestellten biopsychosozialen Rahmens in einem Big Data Ansatz, steht jedoch noch aus. Dieser Ansatz würde es ermöglichen, sowohl biologische Faktoren auf Basis von Training und Wettkampf (d.h. physiologische oder biomechanische Messungen der Ski- und Schießleistung), als auch psychologische Aspekte wie Persönlichkeitsmerkmale, aber auch psychische Zustände oder Aufmerksamkeitsprozesse sowie Informationen soziale Kontextinformationen zu erfassen. Schließlich könnten diese multimethodisch erhobenen Daten (z.B. physiologisches Monitoring, biomechanische Messungen, Selbstauskünfte) mit Leistungsdaten verknüpft werden, um ein tieferes Verständnis dafür zu bekommen, was genau eine*n Olympiasieger*in charakterisiert und welche Faktoren den Unterschied ausmachen, ob man das Podium erreicht oder nicht.

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