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FUNCTIONAL RELATIONSHIPS BETWEEN GAZE BEHAVIOR AND MOVEMENT KINEMATICS WHEN PERFORMING HIGH BAR DISMOUNTS – AN EXPLORATORY STUDY

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ABSTRACT

Purpose. The aims of this study were, first, to investigate visual spotting and, second, to explore the functional relationships between movement structure and gaze behavior in gymnasts as they perform preparatory giant swings (traditional and scooped technique) and dismounts (single straight and double tucked salto) with increasing difficulty on the high bar. It was predicted that visual spotting would occur in all experimental tasks. **Methods.** Relationships between gaze behavior and movement kinematics were explored to provide a clearer picture of how gaze is interconnected with the kinematics of dismounts on the high bar. For this purpose, kinematic parameters were measured with an optical movement-analysis system while gaze behavior was measured by using a portable and wireless eye-tracking system. **Results.** The measurement of gaze behavior revealed that gymnasts use visual spotting in all three tasks showing fixations throughout the whole movement. Each task was furthermore characterized by a sequence of visual fixations that was thought to serve specific movement goals. In particular, fixations during the downswing phase of the preparatory giant swings were significantly correlated with the movement phases when beginning the hip extension and flexion in the "kick through" as well as with the athlete's distance of flight during the dismounts. **Conclusions.** The findings suggest that gymnasts can use visual spotting during preparatory giant swings and dismounts on the high bar and that there are functional relationships between different fixations and specific movement goals.

Key words: gymnastics, giant swings, eye-tracking

Introduction

Intentionally directing one's gaze to objects or locations in a surrounding environment such as gymnastic apparatus, distant walls, the floor or the ceiling is conceptually referred to as *visual spotting* [1]. Visual spotting is thought to play a critical role for optimizing the movement execution of certain skills in sport [2]. It usually accompanies a series of fixations in which the visual system can extract information needed for skill performance [1, 3]. However, little is known about visual spotting and the relationship between visual spotting and movement kinematics in more complex skills that are similar in movement structure but differ in movement dynamics. Therefore, the aim of this study was to investigate visual spotting as well as to explore functional relationships between gaze behavior and movement kinematics in preparatory giant swings and dismounts with increasing difficulty on the high bar.

It has been suggested that the information extracted from visual spotting is primarily used to provide the athlete with information to control the landing of aerial skills [4, 5]. Davlin et al. [4] observed for instance that the landing stability of a back tuck salto was significantly affected by any loss of vision: with no vision yielding worse performance than reduced vision. Luis and Tremblay [6] had experienced acrobats perform back tuck saltos under four different visual conditions: (1) full vision, (2) vision at angular head velocities below $350° s^{-1}$, (3) vision at angular head velocities above $350° s^{-1}$, and (4) no vision. The angular velocity of the head was calculated in real time, triggering liquid crystal goggles to manipulate visual information pickup. It was shown that all vision conditions resulted in better landing performance than the no-vision condition, supporting the assumption that visual information pickup is an important factor which affects gymnasts' performance in aerial skills.

One could, however, argue that manipulating visual information pickup could force gymnasts to rely more strongly on visual spotting and/or to focus their visual attention more intensively [7]. One may additionally assume that the visual information that was manipulated in the previously mentioned studies was either not needed in the performance of the experimental tasks or was related to landing stability only. It could just be the case that when manipulating other visual information, such as the reduction of binocular vision, other parameters may be impacted outside of only landing stability, especially when performing a complex aerial skill. This may at least in part explain why for instance Davlin et al. [4] found no effect on movement kinematics when manipulating visual information pickup.

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It is furthermore argued that during high angular velocities of the head (e.g., during a salto), gaze is not likely to be fixated during a skill, as high angular velocities are thought to exceed the functional range of the vestibulo-ocular reflex in stabilizing the retinal picture [8]. There is, however, additional evidence that athletes' visual systems seem to adapt to training complex skills that incorporate fast whole-body rotations [9]. This may lead to the assumption that rotation trained athletes can extract visual information and/or use adaptive gaze behavior during the performance of skills incorporating fast whole-body rotations. When exhibiting an adaptive gaze behavior, gymnasts would still be able to extract the visual information needed in the performance of the task at hand. As a consequence they would still be able to produce an accurate and precise movement pattern that does not differ from their movement pattern under full vision [9, 10].

Recent work on natural tasks has furthermore demonstrated that the observer's cognitive goals play a critical role in the direction of gaze during a wide range of natural behaviors [3, 11]. It was revealed that subjects usually use eye movements in a proactive manner [12]. Grasso et al. [13] measured the head and horizontal eye movements of individuals walking around corners. It could be shown that when turning, individuals made anticipatory eye and head movements to align with their intended walking trajectory. Hollands et al. [14] had participants walk along a 9-m pathway and measured their gaze behavior and their head and body movements. Participants maintained a straight walking trajectory or changed their walking direction by 30° or 60° at the midpoint of the pathway. The authors found that prior to changing the walking direction, participants aligned their gaze with the end-point of the required travel path. Head and body reorientation accompanied this realignment. These results lead to the assumption that eye movements also during complex skills may be aligned with movement goals. However, empirical evidence concerning this aspect in complex skills, incorporating whole-body rotations, is still lacking.

In summary, performing complex skills with rotations on one or more body axes places specific demands on athletes' spatial orientation [1]. Vision has been proposed to play a critical role in providing athletes with the necessary cues for spatial orientation through visual spotting [4, 6]. However, empirical support on visual spotting and the relationships between gaze behavior and movement kinematics in complex aerial skills is still limited with gaps existing in literature on the subject. Therefore, the goal of the current study was to investigate visual spotting by expert athletes as they perform dismounts with increasing difficulty and the dynamics after preparatory giant swings on the high bar. The athletes' gaze and movement behavior were analyzed in a natural setting in order to determine how their gaze is related to performance [2, 10]. It was predicted that visual spotting would occur in all set tasks, given that athlete's visual system may adapt to training skills incorporating fast whole-body rotations [9]. An additional point of interest was to explore for relationships between gaze behavior and movement kinematics from an exploratory viewpoint, with hopes at providing a clearer picture of how gaze is interconnected with the kinematics of dismounts on the high bar. In contrast to existing research on gaze behavior [15], how distinct fixations may serve specific functions during skill execution were also investigated. It was argued that functional relationships do exist, given that research has demonstrated that participants often use anticipatory eye movements that align with their future (movement) goals [3].

Material and methods

A sample of $N = 12$ gymnasts was recruited to participate in this study. The gymnasts were able to perform dismounts from the high bar with increasing difficulty, such as single and double saltos in tucked, piked or layout body positions with and without twists. The gymnasts were active gymnasts competing in the German 2nd federal league with at least ten years of training and competition experience (age: 23 ± 2 years). It was decided to recruit expert gymnasts and study their movement and gaze behavior in a natural setting in order to determine how athletes' gaze contributes to performance [2]. All participants were informed about the purpose and the procedures of the study and provided their written consent prior to the study. All had normal or corrected-to-normal vision. The study was carried out according to the ethical guidelines and with the approval of the university's local ethical committee.

The experimental tasks were two different backward dismounts on the high bar performed from preparatory giant swings with two different techniques. The general aim of the preparatory giant swings is to achieve sufficient angular momentum together with a sufficient take-off velocity in order to perform the intended dismount. Two distinct techniques for preparatory giant swings have evolved in gymnastics, the *traditional* technique and the *scooped* technique [16]. Both techniques differ with regard to the intensity and timing of extension and flexion of the hip joint and the shoulder joint.

In the *traditional* technique the gymnast maintains a straight body configuration from the handstand position. There is then a slight flexion of the body prior to the bottom of the giant swing, followed by an extension of the body as the gymnast passes under the bar (see Fig. 1). During the upswing phase the gymnast maintains a shallow pike body configuration and extends his body into the handstand [16]. The *scooped* technique is characterized by a flexed body position as the gymnast passes through the horizontal in the downswing phase followed by a hyper-extension of the

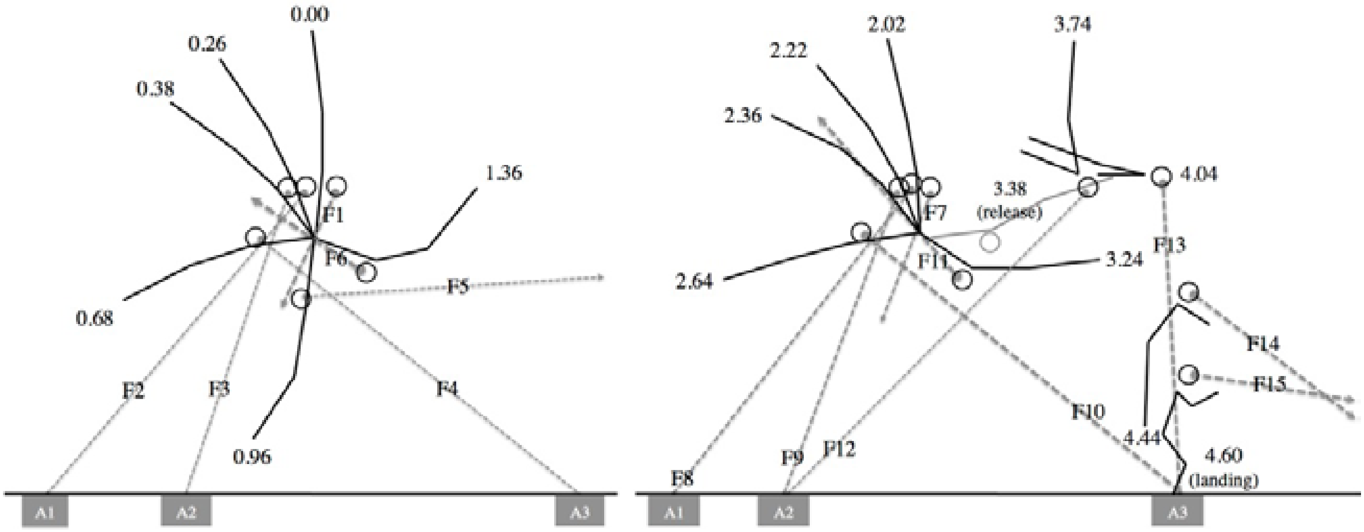

Figure 1. Prototypical stick-figure sequence of the layout salto (right) with a preparatory giant swing (traditional technique) on the high bar (left). The numbers indicate the time structure of the skill. The dotted lines represent the fixations and fixation direction during the skill. The thickness of the dotted lines indicates fixation duration. F1 to F15 indicate the sequence of fixations. A1 to A3 indicate each of the fixation's area of interest that was directly related to movement kinematics

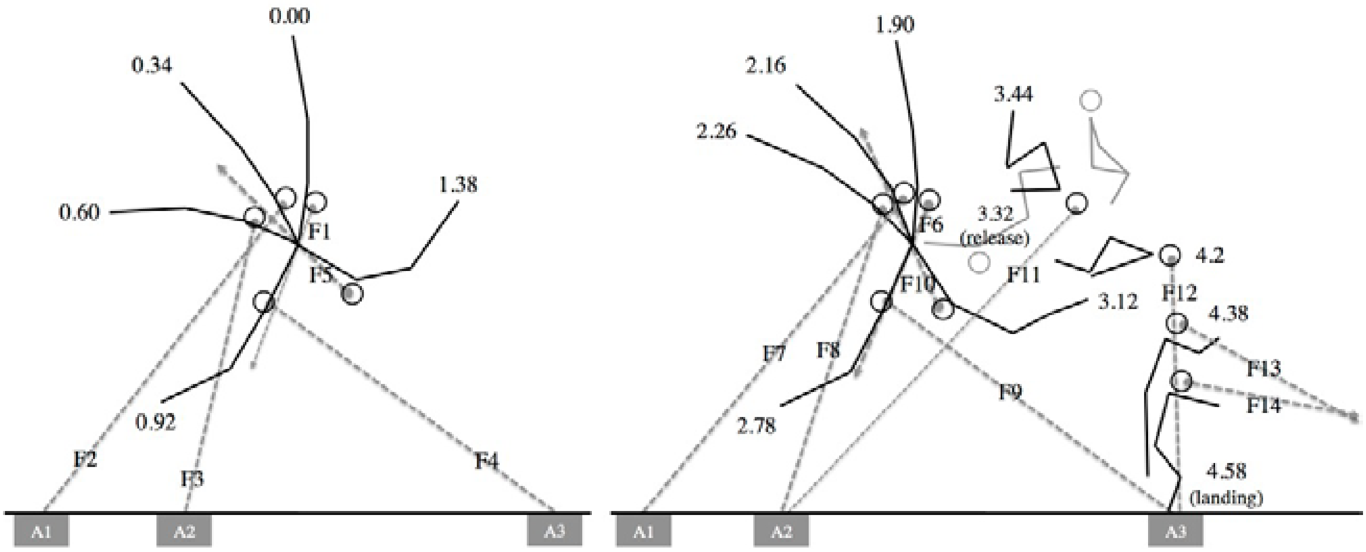

Figure 2. Prototypical stick-figure sequence of the double salto (right) with a preparatory giant swing (traditional technique) on the high bar (left). The numbers indicate the time structure of the skill. The dotted lines represent the fixations and fixation direction during the skill. The thickness of the dotted lines indicates fixation duration. F1 to F14 indicate the sequence of fixations. A1 to A3 indicate each of the fixation's area of interest that was directly related to movement kinematics

hip [17]. The "kick through" is delayed compared to the traditional technique, and appears as an accentuated piking action late in the upswing, which continues over the top of the bar (Fig. 2). Both techniques are appropriate to produce large amounts of angular momentum [18]. However, the scooped technique may be more functional during the gymnast-bar system energy exchange, especially when the aim is to maximize angular momentum and to optimize flight time during the dismount [19]. The scooped technique may also be advantageous by providing a wider release window and, therefore, provide a greater margin of error than the traditional technique [17].

It was decided to use both the traditional technique and the scooped technique in two different dismounts (single backward salto in a layout body configuration vs. double backward salto in a tucked body configuration) in order to answer the question of how gaze behavior is related to performance depending on the dynamics of both the preparatory giant swings and dismounts. This resulted into the three experimental conditions: (1) single salto in a layout body configuration (tradi-

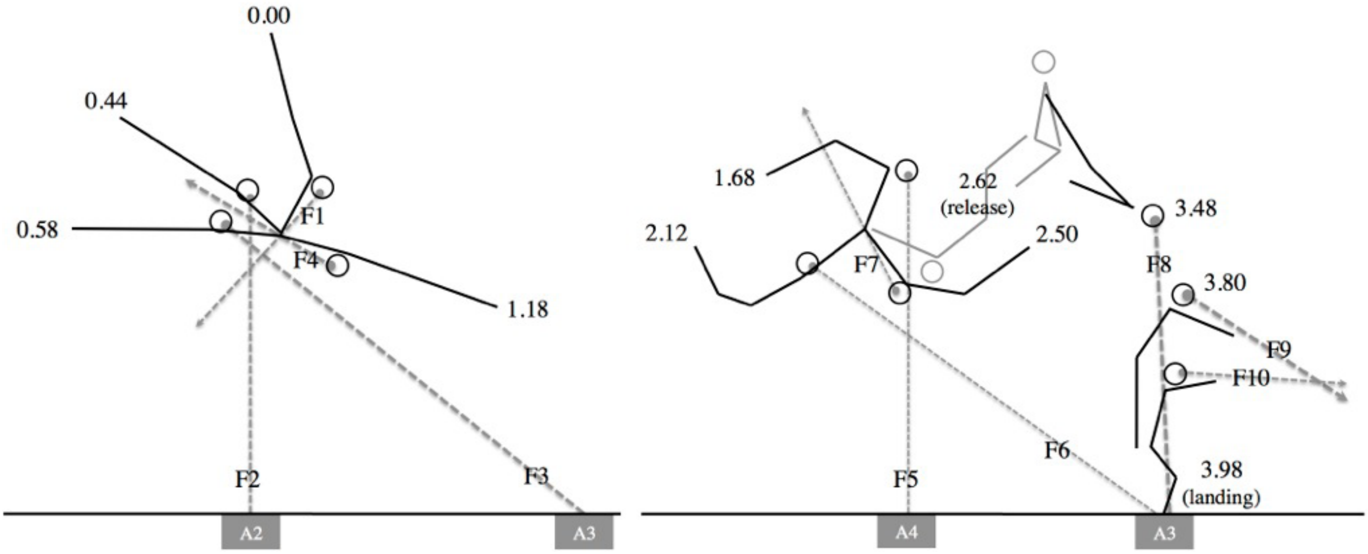

Figure 3. Prototypical stick-figure sequence of the double salto (right) with a preparatory giant swing (scooped technique) on the high bar (left). The numbers indicate the time structure of the skill. The dotted lines represent the fixations and fixation direction during the skill. The thickness of the dotted lines indicates fixation duration. F1 to F14 indicate the sequence of fixations. A1 to A4 indicate each of the fixation's area of interest that was directly related to movement kinematics

tional giant swing technique, Fig. 1), (2) double salto in a tucked body configuration (scooped giant swing technique, Fig. 2) and (3) double salto in a tucked body configuration (traditional giant swing technique, Fig. 3).

The gymnasts were videotaped in order to allow for further kinematic analysis. The horizontal and vertical coordinates of nine points (body landmarks) were recorded in each frame using movement analysis software (WinAnalyze 3D, Mikromak, Germany) [20]. The nine body landmarks were used to define a 7-segment model of the human body. As the three chosen tasks only contain regulatory low frequency movements, a frame rate of 50 Hz was deemed sufficient for kinematic analysis of the high bar performances by an independent biomechanist. A digital filter (cutoff frequency of 6 Hz) was applied for data smoothing. A mean temporal error of ± 0.02 s and a mean spatial error of ± 0.007 m were calculated from the present data. The body-segment parameters were calculated on the basis of the individual anthropometric properties of each participant.

The swing motions prior to release in the traditional and scooped technique are characterized by a particular coordination of the hip and shoulder joints [18]. In order to describe the *timing* of the giant swings and the dismounts, the relative phase durations were analyzed. Changes in *body configuration* during the movement phases were expressed by the values of the shoulder angle and the hip angle [21]. Finally, the *landing* was expressed by calculating the distance of the feet to the high bar during touch-down.

A recently developed recording system was used to record eye movements [10]. The system consists of a modified bicycle helmet with an attached wireless infrared miniature camera (approximate weight 250 g). The miniature camera records images of the eyeball at a sampling rate of 50 Hz, and can be synchronized with the WinAnalyze 3D movement-analysis system. The eyeball is illuminated by two infrared diodes that create two reflection points on the cornea. The X- and Y-coordinates of both corneal reflection points, the centroid of the pupil, and another reference point (inner side of nasal bone) were digitized in a semi-automatic manner. From the coordinates of the reference points, camera movements that occur during complex movements were then mathematically corrected. The rotation of the eyeball was calculated from the corneal reflection points and the centroid of the pupil. Angular data of the eyeball was then integrated into the kinematic data from the movement analysis system and the current gaze direction was superimposed on the digital video sequences of the saltos. Eye movement measurement error was given as 0.5° between –15° and +15° of the visual field in the horizontal and the vertical directions and 1.0° between +15° to +30° and –15° to –30° of the visual field in the horizontal and the vertical directions.

In this study, two gaze behavior variables were analyzed: the direction and duration of the visual fixations. A fixation was defined as any state in which the gaze remains stationary on one reference point in the environment for five video frames or longer (100 ms) [22]. During a giant swing or salto this may occur especially when the eyes rotate to compensate for rotations of the head in order to hold the gaze fixated on one reference point. Two independent and trained research assistants coded the visual fixations and eye blinking frame by frame. Inter-rater reliability was calculated at $r = 0.91$ ($p \leq 0.05$). In order to analyze how gaze behavior was connected with movement behavior, the gymnast's gaze behavior and movement kinematics were averaged over all trials for each of the three dismounts. From this average, prototypical stick-figure sequences were generated, indicating the distinct fixations to the same areas of interest that occurred in more than 68% of the trials [23]. As a last step, product-moment correlations were calculated between kinematic parameters and gymnasts gaze behavior.

The high bar used in the experiment was arranged as it would be in an international competition with safety mats in the front, below and behind the high bar. Each participant took part in two familiarization trials without the use of the eye-tracking helmet and another three trials with it in order to get used to the equipment. There was no time pressure in this study and each participant was allowed to take breaks as needed. After the familiarization trials, the participants were asked to perform the experimental tasks in a random order. The participants were instructed to perform a landing as per gymnastic rules at the end of the dismount and then stabilize their landing for at least three seconds. Each participant was asked to perform four dismounts of each of the studied saltos for a total of twelve dismounts.

Results

As this study attempted to explore the relationships between gaze behavior and movement kinematics, the results of both were averaged over all the trials performed by all participants for each of the three dismounts. Figures 1, 2 and 3 present the prototypical movement sequences together with visual fixations on specific areas of interest in the layout salto, the double salto (traditional technique) and the double salto (scooped technique), respectively.

A prototypical *layout salto* with the *preparatory giant swing* was characterized by a sequence of 15 fixations, starting during the handstand position of the preparatory giant swing and ending during the landing. The first, sixth, seventh and eleventh fixation were directed toward the high bar. The second, third, eighth, ninth, and twelfth fixations were directed toward the rear mat. The fourth, tenth and thirteenth fixations were directed towards the front mat. The fifth fixation was directed towards the distant wall in front of the gymnast, and the fourteenth and fifteenth fixations were also directed towards the front mat. Three significant correlations were found that seemed to be of high functional relevance. First, the direction of the second and eight fixations were significantly correlated ($r = 0.85$, $p \leq 0.05$) with the moment of when the hip extension began during the preparatory giant swing and during the downswing prior to the dismount, which indicates the starting point of the kick through. A correlation of $r = 0.87$ ($p \leq 0.05$) was found between the direction of the third, ninth and twelve fixations and the moment when the hip joint started to be flexed in order to perform the kick through. Finally, the fixation direction of the fourth, tenth and thirteenth fixations was significantly correlated with the athlete's distance of flight ($r = 0.91$, $p \leq 0.05$).

A prototypical *double salto* performed with the *traditional giant swing technique* was characterized by a sequence of 14 fixations. The first, fifth, sixth and tenth fixations were directed towards the high bar. The second, third, seventh, eighth and eleventh fixations were directed towards the rear mat. The fourth, ninth, twelfth, thirteenth and fourteenth fixations were directed towards the front mat. In line with the results reported for the layout salto, again, significant correlations were found that seem to be of high functional relevance. First, the direction of the second and seventh fixations were, on average, significantly correlated ($r = 0.87$, $p \leq 0.05$) with the moment of when the hip extension began during the preparatory giant swing and during the downswing prior to the dismount, indicating the starting point of the kick through. An average correlation of $r = 0.86$ ($p \leq 0.05$) was found between the direction of the third, eighth and eleventh fixations and the moment when the hip joint started to be flexed in order to perform the kick through. Finally, the fixation direction of the fourth, ninth and twelfth fixations was significantly correlated with the athlete's flight distance ($r = 0.90$, $p \leq 0.05$).

A prototypical *double salto* performed with the *scooped giant swing technique* was characterized by a sequence of 10 fixations. The first, fourth and seventh fixations were directed towards the high bar. The second fixation was directed toward the rear mat. The third, fifth, sixth and eighth fixations were directed towards the front mat. Similar to the results of the layout salto, again, three significant correlations were found that seemed to be of high functional relevance. First, the direction of the second fixation was significantly correlated ($r = 0.87$, $p \leq 0.05$) with the moment when the hip extension began during the preparatory giant swing. The moment when straight body posture was achieved prior to the flexion of the hip during the upswing of the dismount was significantly correlated with the direction of the fifth fixation ($r = 0.75$, $p \leq 0.05$). Finally, the fixation direction of the third, sixth and eighth fixations were, on average, significantly correlated with the athlete's flight distance during the dismount ($r = 0.89$, $p \leq 0.05$).

Discussion

The goals of the current study were to investigate visual spotting in gymnasts as they perform complex rotational movements with increasing difficulty and to explore the functional relationships between movement kinematics and gaze behavior. Gymnasts' gaze behavior and movement kinematics were measured while they performed three different dismounts on the high bar. It was predicted that visual spotting would occur in all experimental tasks. Additionally, relationships between gaze behavior and movement kinematics were explored to provide a clearer picture of how gaze is interconnected with the kinematics of dismounts performed on the high bar.

The measurement of gaze behavior revealed that gymnasts use visual spotting in all three tasks because they show fixations throughout the entire movement. Visual fixations on informational aspects that are relevant for movement control when specific constraints are met could be part of a perceptual strategy to control preparatory giant swings and dismounts on the high bar [10]. Gymnast experts may optimize their visual information pickup in different movement phases because they know better "where" to look and "what" to look for [24, 25]. An optimized visual information pickup system could in turn lead to optimized movement planning and regulation [26]. Land and Furneaux [3] concluded from eye movement research in a wide variety of tasks that both motor skills and eye movements are specific to particular set tasks, and it seems sensible to think of eye movements as an integral part of each skill. The authors, furthermore, state, "The eye must be told where to look, what to expect there, and what further observations or measurements to make" [3, p. 1238]. This may explain why correlations between gaze direction and the spatial parameters of significant movement events were found in the present study.

One main result of our study was that fixations during the downswing phase of the preparatory giant swings were significantly correlated with the moment at the beginning of hip extension and flexion in the "kick through", as well as with the athlete's flight distance during the dismounts. There were additional significant correlations between the athletes' flight distance and fixation direction during the last phase of the dismounts. For instance, a correlation between fixation direction and landing position during the preparatory giant swing could indicate that gymnasts try to pick up visual information related to the (intended) landing position already during the preparatory giant swings and integrate this information with their current movement state in order to prepare for the dismount. The same argument could hold true for controlling hip extension and hip flexion during the preparatory giant swing. Vision is the only human sensory modality capable of providing information about distant environmental features [27]. Such a characteristic may account for visual information being used in a feed-forward manner to modulate movement patterns, thereby allowing gymnasts to reach their specific goals in a specific environment, such as the defined extension-flexion movement of the hip in a given time window during the giant swing prior to the dismount. This may also explain the fixations made on a landing position during the flight phase of the dismounts. Most likely they serve as a function that prepares the gymnast for the landing phase.

The differences in gaze behavior between the different tasks may, however, reflect the ability of experienced athletes to guide eye movements proactively, in anticipation of events that are likely to occur [12]. Since the experimental tasks differed in their dynamic structure (e.g., traditional vs. scooped technique), it can be assumed that the participants had to rapidly adapt their motor behavior to make optimal use of whatever sources of information available in their movement environment in order to solve the experimental task [28]. However, in regards to the complex skills in gymnastics, it has been argued that skilled participants do not rely on whatever sources of information that are available, but rather use information in the movement environment that is more closely related to movement execution in terms of temporal and/or spatial parameters [1].

There are a number of critical issues present in the experiment that need to be taken into account, with three specific aspects that need to be emphasized. First, visual information pickup was not manipulated, where only athletes' gaze behavior was analyzed in a natural environment as to better understand how gaze behavior contributes to complex movement execution. Manipulating visual information pickup, while concurrently measuring gaze behavior, could reveal if it leads to adaptive gaze behavior that masks the effect of visual manipulation. Second, a sample of $N = 12$ participants was recruited. It must be acknowledged that this is a potential limitation with regards to the present results. However, a power analysis on the results revealed that the average power for all significant results was above .80, which can be assumed as sufficient given the design of the present study [29]. Third, it must be acknowledged that the correlative relationships found between movement kinematics and gaze direction may not be interpreted in a causative manner [30]. Nevertheless, these correlations may serve in creating new hypotheses when assessing the interaction of gaze and movement behavior in gymnasts.

As a final note, assuming that athletes can extract information on orientation by anchoring their gaze on objects or areas within their environment, coaches should encourage athletes to intentionally use visual spotting when practicing giant swings and dismounts.

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