PREPRINT: A temporal quantitative analysis of visuomotor behavior during different twisting somersaults in elite and sub-elite trampolinists

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Abstract

To perform twisting somersaults and land safely, athletes need advanced spatial orientation skills in which vision might play a key role. Elite gymnasts translate more accurately the visual information into an appropriate kinematic response, thereby increasing their performance. Due to this link between vision and performance, it appears of interest to better understand the visuomotor strategies used by athletes during acrobatics as it could help coaches better guide their athletes through visuomotor skill development. The present study sought to identify the differences in gaze behavior between elite and sub-elite trampolinists during the execution of four acrobatics of increasing difficulty. Seventeen trampolinists (8 elites, 9 sub-elites) were equipped with 17 inertial measurement units and a wearable eye-tracker. Firstly, six typical metrics extracted from their body and gaze kinematics were analyzed. A mixed analysis of variance (ANOVA) was performed with the *Expertise* as inter-subject and the *Acrobatics* as intra-subject factors. Only one significant difference was observed in the *Expertise* factor: elite athletes fixated their gaze more often than sub-elite athletes ($p=0.033$), although the fixation durations were not different between the two groups. Secondly, to complement the understanding of trampolinists' visual strategies, more advanced eye-tracking metrics were analyzed: the dwell time on areas of interest, the scan path on the trampoline bed, the temporal evolution of the gaze orientation endpoint (SPGO), and the time spent executing specific neck and eye strategies. Large inter- and intra-individual visuomotor variabilities were observed in the SPGO, which suggests that an ideal visual strategy to perform acrobatics does not exist. Notably in this study, while analyzing the combined eyes and neck movements, it was possible to confirm the use of *spotting* at the beginning and end of the acrobatics and to reveal a unique sport-specific visual strategy that we termed *self-motion detection*, which consists in not moving the eyes during fast head rotations. *Self-motion detection* was mainly used during the twisting phase of the acrobatics. This study proposes a thorough exploration of trampolinists' gaze behavior in highly ecological settings and contributes to enhancing the understanding of visuomotor strategies adopted during the execution of twisting somersaults.

Keywords – Gaze, Acrobatics, Expertise, Visual strategies, Eye-tracking, Skill acquisition

Highlights

- Elite athletes used more tracking fixations than sub-elite athletes.
- Trampolinists changed their visuomotor strategies depending on the acrobatics.
- Trampolinists mainly fixated their gaze on the trampoline bed.
- Trampolinists' visual strategies presented an important execution variability.
- Trampolinists used a newly discovered visual strategy wherein their eyes remained fixed while their body (including their head) was rotating in the air.

1 Introduction

Acrobatic sports require athletes to perform complex movements in the air, often involving high angular velocities across multiple axes. The execution of these acrobatics is highly dynamic and must respect the constraints of the task (*e.g.*, body posture imposed by the code of points FIG Executive Committee (2021)), the athlete's own individual physical capabilities (*e.g.*, flexibility), as well as environment-related constraints (*e.g.*, land on the most central part of the trampoline). In trampolining, an important challenge is to land each acrobatic on the center of the trampoline with accurate body orientation and velocity to initiate the next one properly. As angular momentum is preserved throughout the aerial phase of acrobatics, the appropriate landing conditions are met through inertia modifications achieved by moving the limbs. To execute appropriate limb movements, refined spatial orientation skills are required. Acrobatic athletes of a higher expertise class can identify more accurately their body orientation in space due to more developed sport-specific skills (Heinen et al., 2018). It is thought that spatial orientation might be largely achieved by picking up visual information from the environment. In fact, athletes often report making *visual contact* with specific elements of their environment during their acrobatics to guide their body kinematics. This need for visual information was experimentally confirmed in multiple studies. As such, the availability of visual information (eyes opened *vs* blindfolded) has been found to decrease landing variability, increasing successful landing rate (Davlin et al., 2004; Heinen and Veit, 2020; Rezette and Amblard, 1985; Bardy and Laurent, 1998; Davlin et al., 2001b). Therefore, it is assumed that athletes need to make appropriate motor adjustments according to their identified self-orientation in space to achieve more consistent landings. This emphasizes that athletes rely on perceptual, cognitive, and motor skills when making embodied choices (Raab and Araújo, 2019; Voigt et al., 2023).

The ability to pick up the appropriate sensory information in the environment, to interpret it, in order to execute an appropriate action is referred to as perceptual-cognitive skill (Davids et al., 2005). It is strongly believed that to study perceptual-cognitive skills in sports, it is crucial to choose an experimental design that maintains a high level of representativeness to the actual learning environment, especially allowing high action fidelity to the task being measured, such as perception-action coupling (Pinder et al., 2011). For example, it was previously shown that the experimental setup can have an impact on the visual strategies used by athletes (Mann et al., 2007; Dicks et al., 2010). To better understand the importance of perceptual-cognitive skills in sports performance, researchers have investigated how they develop through age (De Waelle et al., 2021) or differ between expertise levels (Mann et al., 2007), in sport-specific contexts. In gymnastics more specifically, it was observed that elites had a greater increase in acrobatic success rate when visual information was made available during a standing backward somersault on the floor, suggesting that their information pick-up strategies led to better prospective regulation of the acrobatic movement (Bardy and Laurent, 1998). It is therefore relevant to ask: What are the best information pick-up strategies leading to better execution and regulation of acrobatic movements? Spotting was found to be one of the first pieces of answer. Heinen & al. observed that athletes partly compensated their body rotation with opposite neck rotation during high bar dismounts (Heinen et al., 2012b) and back somersaults (Heinen, 2011), respectively. This behavior reduces the head angular velocity, slowing down the retinal flow which provides a greater resolution of the information projected on the retina. This task-specific visuomotor strategy was identified only through an analysis of the body kinematics (*i.e.*, without gaze analysis). However, measuring both the eye and body kinematics might help us better understand the visuomotor behavior of acrobatic athletes as it might allow the identification of other acrobatic-specific strategies combining body, head, and eye movements. A holistic approach combining eye and body kinematic analysis could help highlight the intertwining of perception and action during embodied choices (Voigt et al., 2023).

Wearable eye tracking devices are useful for identifying toward which element of the environment the athletes chose to orient their gaze to pick up the information (Lappi, 2015). Interestingly, it can be used in an ecological context to record the temporal evolution of the eye orientation without interfering too much with sports practice, even during high-velocity head movements such as during acrobatics (Hüttermann et al., 2018). In trampoline, only three studies were carried out using an eye tracker in ecological settings to acquire straight backward somersaults with a full twist (Natrup et al., 2021), tuck backward somersaults (with and without kick-out) (Natrup et al., 2020), and back tuck somersaults (without preparatory jumps and with a flight time constrained to 1 s) (Heinen, 2011). Overall, they found that trampolinists look at the trampoline bed before landing (Natrup et al., 2021, 2020) and that the fixation position on the trampoline bed depends on the landing horizontal position (Natrup et al., 2020). Natrup et al. (2021, 2020) found that athletes of higher expertise fixated their gaze on the trampoline bed later, resulting in a shorter fixation before landing. This behavior was attributed to the compliance of elite athletes with the sport's regulations prescribing a neutral head posture. It was observed that athletes of all expertise levels used spotting, and elite athletes spent a larger portion of their acrobatics fixating compared to sub-elites (Heinen, 2011). These studies have paved the way for a better understanding of visuomotor strategies in trampolining. However, they were limited in two ways.

First, each finding only relied on one single acrobatics which limits the application of knowledge in regards to visuomotor skill development as it cannot be assumed that the same principles apply to different acrobatics. As previously suggested, visuomotor strategies in acrobatics seem to be dependent on the task constraints (Barreto et al., 2021; de Carvalho Barreto et al., 2020). In this regard, identifying common strategies across acrobatics would be valuable to coaches, therefore study designs should include the assessment of multiple acrobatics. Second, the temporal data from previous studies was reduced to scalar metrics (also referred to as "0D"). Quantitative eye tracking studies typically reduce the temporal evolution of gaze coordinates to secondary metrics for statistical analysis. These are usually presented in the form of the number of fixations and saccades, or the duration of fixations, saccades and quiet eye (Holmqvist and Andersson, 2017; Klostermann and Moeinirad, 2020). However, this type of data treatment might not preserve all the subtleties of gaze behaviors (Klostermann and Moeinirad, 2020). In fact, the use of scalar metrics like fixation duration has been recently questioned because they might not reflect the continuous nature of visual strategies during sporting tasks (Klostermann and Moeinirad, 2020). As such, secondary metrics alone may not capture the complexity of the athletes' visual strategies. Instead, it was shown in other fields, such as biomechanics, that analyses based on time series metrics (also referred to as "1D") are more prone to identifying differences in behavior between groups than 0D metrics, especially when the knowledge of the research topic is sparse (Pataky et al., 2016). Using time series which preserves the continuous nature of acrobatic sports movements, would better reflect the actual behavior employed by athletes and would simplify the transfer of knowledge to coaches. Although a few studies have assessed the visuomotor behavior of trampolinists in ecological settings with scalar metrics, to our knowledge, none has ever explored the visuomotor strategies of acrobatic athletes by analyzing 1D metrics.

Addressing the above-mentioned limitations could enhance the understanding of visuomotor strategies in trampoline which could improve the coaching knowledge for the development of more effective skill learning practices. Examining the visuomotor behavior of elite athletes could also help coaches guide sub-elite athletes towards more efficient strategies (Vine and Wilson, 2011). In this perspective, the current study had three objectives. Firstly, it aimed to assess the influence of expertise on trampolinists' visuomotor behaviors during different twisting somersaults of increasing difficulty. We hypothesized that: *i)* elite athletes would make a similar number of fixations but of shorter duration compared to sub-elites, similar to previous findings (Natrup et al., 2021, 2020), *ii)* elite athletes would use neck movements of smaller amplitude considering the smaller maximal neck angle observed by Natrup et al. (2021), and consequently *iii)* elite athletes would compensate by using eye movements of greater amplitude. Secondly, this study proposed to use a 1D approach to analyze the gaze endpoint time series, following recent recommendations (Klostermann and Moeinirad, 2020; Kredel et al., 2017). It was expected that differences in visuomotor strategies induced by expertise would be more emphasized by the 1D metrics analysis, compared to 0D. Thus, it was anticipated that *iv)* the temporal evolution of the gaze orientation of elite and sub-elite athletes would be different due to strategy refinement arising from sports expertise. Thirdly, this study aims to synthesize the visuomotor behavior of trampolinists during four types of twisting somersaults to improve coaches' knowledge of the strategies used by athletes during acrobatics. With this goal in mind, significant effort will be devoted to detailing these visuomotor strategies from an applied perspective.

2 Methods

2.1 Participants

Eight elite (4 males and 4 females; mean±SD: 22.3±4.7 years old) and nine sub-elite (3 males and 6 females; 15.3±2.1 years old) trampolinists were recruited to participate in this study. The expertise inclusion criteria were based on the national federation guidelines (GymCan, 2021) and the first author's national coaching experience. Elite athletes could perform at least three different twisting double somersaults whereas the sub-elite athletes had never completed a double somersault with more than ½ twist and could perform single somersaults with up to 1½ twists. All athletes had normal or corrected to normal vision (acuity $\leq$ 20/20 on a Snellen test) and had a good 3D vision (stereoscopy $\leq$ 70" on a Randot test) following a visual examination occurring before the evaluation session. Athletes were excluded if they suffered from a musculoskeletal injury at the time of the data collection or if they sustained a concussion within the three months preceding data collection. Athletes did not wear eye makeup and had to limit their coffee consumption to two servings on the day of the data collection. The protocol (No. CERC-19-002-D) was approved by the Université de Montréal Research Ethics Committee. Participants and tutors (for minor participants) gave their verbal and written informed consent to participate.

2.2 Experimental procedure

Athletes were first instructed to warm up freely on the floor and trampoline for 5-15 min at their convenience while equipped with measuring devices (Sec. 2.3) for acclimation. Then, each athlete repeated the four acrobatics of interest (Fig. 1) at least five times (Tab. 1). The acrobatics were composed of one somersault rotation in straight position and 0 ($Acro\ ^{0\ twist}_{back}$), $^1/_2$ ($Acro\ ^{1/2\ twist}_{front}$), 1 ($Acro\ ^{1\ twist}_{back}$), or $1^1/_2$ ($Acro\ ^{11/2\ twist}_{front}$) twist rotations. The acrobatics were paired two-by-two ($Acro\ ^{0\ twist}_{back}$ & $Acro\ ^{11/2\ twist}_{front}$ and $Acro\ ^{1/2\ twist}_{front}$ & $Acro\ ^{1\ twist}_{back}$) to form a 10-skill sequence of acrobatics as found in competition (FIG Executive Committee, 2021) to maintain high representativeness towards the requirements of the trampoline demand. Ideally, the athletes performed the 10 acrobatics in a row; if an athlete was not able to complete the 10-skill sequence, it could be decomposed into multiple smaller sequences summing up to 10 acrobatics. The sequence order was randomized between athletes to avoid any potential fatigue effect.

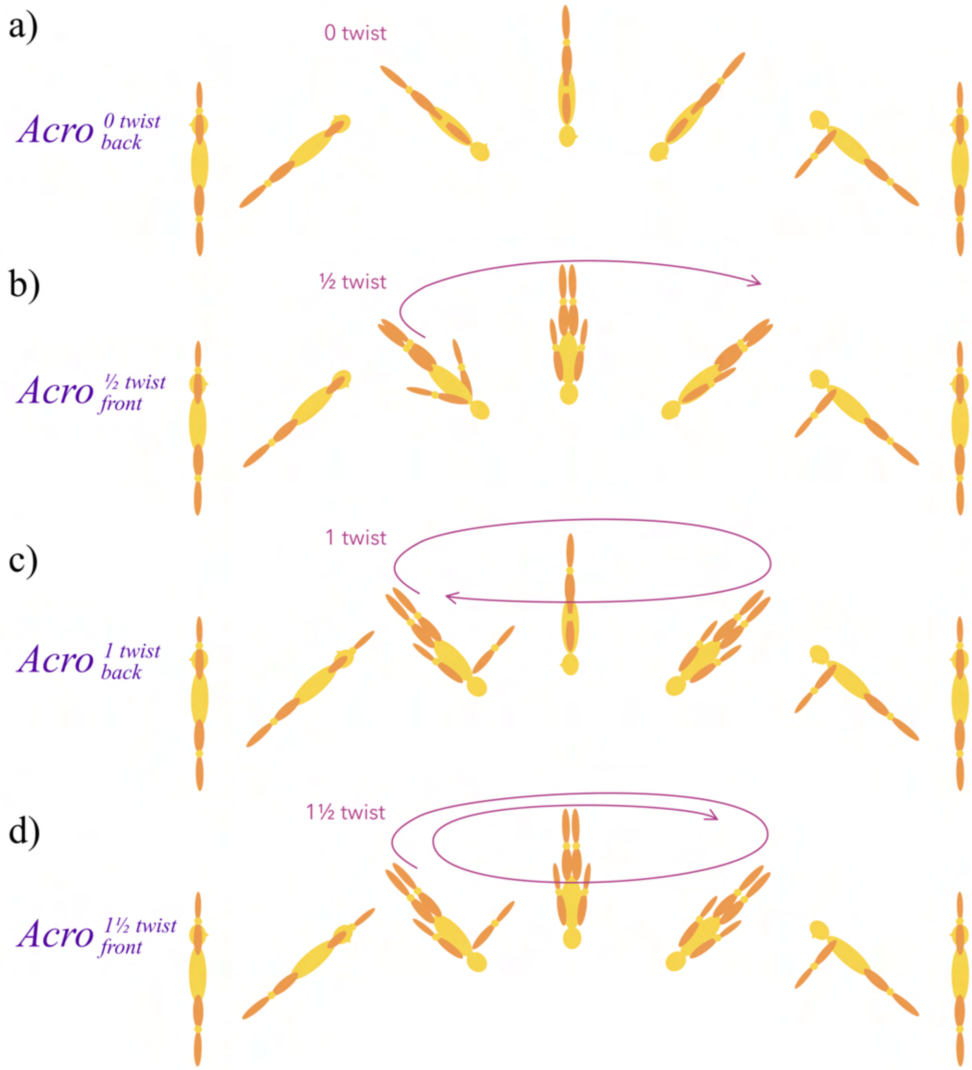


Figure 1. The four acrobatics performed by elite and sub-elite trampolinists. All acrobatics were composed of one somersault rotation in straight position with 0 to $1^1/_2$ twists.

A recovery break of 30 s to 5 min was allowed between trials at the athlete's convenience. Acrobatics that did not end on the trampoline bed (*e.g.*, ending on the safety mat, end deck mats, or pads) or did not respect the requirements of the acrobatics (*e.g.*, inappropriate number of somersaults or twists) were excluded from the analysis and the athletes were instructed to perform the unsuccessful acrobatics again until full completion of the sequence. To avoid fatigue, the duration of the testing on the trampoline did not exceed 90 min. To comply with this constraint, the testing of three elite athletes was separated into two sessions on different days.

Table 1. Number of trials that each athlete performed per acrobatic.

Athlete	Expertise level	$Acro^{0\ twist}_{back}$	$Acro^{1/2\ twist}_{front}$	$Acro^{1\ twist}_{back}$	$Acro^{1 1/2\ twist}_{front}$
Sub-elite #1	Tier 2	9	10	10	9
Sub-elite #2	Tier 2	9	8	8	9
Sub-elite #3	Tier 2	7	10	10	6
Sub-elite #4	Tier 2	10	10	10	10
Sub-elite #5	Tier 2	10	10	10	10
Sub-elite #6	Tier 2	10	12	10	10
Sub-elite #7	Tier 2	9	12	10	9
Sub-elite #8	Tier 2	10	10	10	10
Sub-elite #9	Tier 2	12	10	10	11
Elite #1	Tier 3	16	10	10	15
Elite #2	Tier 5	10	14	14	10
Elite #3	Tier 3	8	10	10	7
Elite #4	Tier 5	12	5	5	10
Elite #5	Tier 3	11	10	10	11
Elite #6	Tier 4	10	12	12	10
Elite #7	Tier 5	5	10	10	10
Elite #8	Tier 3	10	14	5	0*

Note: Athletes were classified according to the Participant Classification Framework (McKay et al., 2022), where tier 2 = Trained/Developmental, tier 3 = Highly Trained/National Level, tier 4 = Elite/International Level, and tier 5 = World Class athletes.

* One elite athlete refused to execute one acrobatics for personal reasons. For the statistical analysis, this specific athlete was attributed the mean value of the expert group for this acrobatics.

2.3 Apparatus

A wearable eye tracking device (Pupil Invisible, Pupil Labs, Germany) measured the athletes' gaze behavior at a frequency of 200 Hz with a field of view of 82° × 82°. All athletes performed the acrobatics on the same competition FIG-certified trampoline (Ultimate, Eurotramp, Germany) at a Canadian national sports institute. Seventeen inertial measurement units (IMUs; MTw, Xsens Technologies B. V., Netherlands) were positioned on the athletes' limbs according to the Xsens system instructions (Fig. 2). The IMUs measured the athletes' kinematics at a frequency of 60 Hz, which allowed extracting head and neck movements, and the center of mass (CoM) trajectory. The measuring devices were maintained in place with tape, elastic bands, and hair clips to prevent them from moving during trials.

Figure 2. Illustration of a trampolinist equipped with the 17 IMUs and the wearable eye tracker (left). The IMUs were covered with elastic bands to fix them on the athlete's segments (right).

2.4 Raw data treatment

The gaze orientation was reconstructed from the eye tracking data using Pupil Invisible's software (Tonsen et al., 2020) and the athletes' body kinematics were reconstructed using MVN Analyze software (Schepers et al., 2018). All of the following data treatment was then performed with custom-made open-source Python code (Charbonneau et al., 2023). The summed acceleration profile from all IMUs and the first-person view video footage from the eye tracker were used to identify take-off and touch-down event timestamps during the preparatory jumps. Off-line synchronization of the two systems was performed by optimizing the alignment of the take-off and touch-down timestamps.

2.5 Gaze orientation data treatment

Three main data treatments were used to extract metrics that were considered more suitable for quantitative characterization of the visuomotor behavior of the trampolinists.

Blinks detection. Video footages of the pupils were manually classified to identify eye blinks (*i.e.*, when the eyelids covered the pupil entirely). During blinking events, the gaze orientation was not considered for analysis.

AOI classification. The gymnasium environment was divided into AOIs based on the geometry of the environment to facilitate the interpretability of the results for coaches. Six AOIs were retained: *1)* the trampoline bed, *2)* trampoline mats around the trampoline bed, *3)* ceiling, *4)* athlete's own body, *5)* front and back walls, and *6)* right and left walls. The gaze was projected on the athlete's point of view video footage recorded by the eye tracker. Each frame was manually classified according to the AOI where the athletes oriented their gaze. The dwell time on each AOI was reported.

Scan path on the trampoline bed. Since it was previously reported that athletes fixate their gaze on the trampoline bed to orient themselves during acrobatics (Heinen and Veit, 2020; Natrup et al., 2021, 2020), special attention was granted to visualize where the athletes looked on the trampoline bed surface using heat maps of the gaze orientation. The minor and major axis lengths of the smallest ellipse containing 90% of the heat map were reported as a measure of the dispersion of the gaze orientation (see Appendix A for the detailed method).

2.6 Gaze orientation and kinematics data treatment

To represent the gaze orientation in the gymnasium reference frame, the eye angles were connected to the body kinematics (see https://osf.io/nkbps/ for a video). This combination of gaze orientation and body kinematics was used to retrieve the temporal evolution of the gaze orientation endpoint in the gymnasium (see Appendix B for the detailed method). The following visuomotor metrics were then extracted: symmetrized projected gaze orientation (SPGO), number and duration of tracking fixations, duration and onset of the quiet eye, integrated neck and eye deviations, and proportion of specific neck and eye strategies.

SPGO represents the temporal evolution of the gaze endpoint on the symmetrized gymnasium walls. The SPGO was chosen for its simplicity of interpretation and its direct link to visuomotor strategies.

Tracking fixations were used instead of traditional fixations due to the large head movements induced by acrobatic movements. Tracking fixation refers to the stabilization of the gaze on a specific zone of the environment (Lappi, 2015), while traditional fixation refers to the stabilization of the gaze in the head reference frame. Tracking fixations were numerically characterized by periods of 40 ms (King et al., 2019) where the temporal evolution of the projected gaze orientation was within the stability threshold defined by:

$$\Delta p_{max} = tan(5^{\circ}) * \overline{d} \tag{1}$$

where Δp_{max} is the maximal deviation from the mean projected gaze orientation over the period and $\overline{d}$ is the mean distance between the eye position and the projected gaze orientation over the period.

If the identified 40 ms tracking fixation periods were overlapping or consecutive, they were joined together to form one larger tracking fixation period. Note that a drift of the mean projected gaze orientation was accepted during these larger tracking fixations, leading to possible non-respect of Eq. 1 over the whole duration of the longer tracking fixation. The number and duration of tracking fixations were reported. For comparison purposes, all the duration and timing metrics reported in this article were normalized over the duration of the acrobatics. Even though fixations are usually analyzed in combination with saccades, this metric was left aside in the current study. The large head rotation induced by acrobatic movements made it too difficult to identify saccades with an acceptable error rate.

Quiet eye is usually defined as the duration of the last fixation on a specific location before movement initiation (Rienhoff et al., 2016). In the current study, the last tracking fixation on the trampoline bed before landing was classified as a quiet eye. The landing was identified as a key phase of the acrobatics since a small postural error during landing may lead to large consequences on the next acrobatics. This suggests that large attentional resources would be needed to prepare for landing, which may imply a longer fixation of the gaze on a strategic area of the trampoline bed before touchdown. To confirm this hypothesis, a paired two-way analysis of variance (ANOVA) was carried out with a within individual *Acrobatics* factor ($Acro\,^{0\ twist}_{back}$, $Acro\,^{1/2\ twist}_{front}$, $Acro\,^{1\ twist}_{back}$, $Acro\,^{1 1/2\ twist}_{front}$) and a *Fixation type* paired factor (mean fixation duration *vs* quiet eye duration). The mean tracking fixation duration was compared with the quiet eye (last tracking fixation) duration for each *Acrobatics*. The results confirmed that the last tracking fixation duration before landing was longer than the mean tracking fixation duration ($F[1,16]=48.85$, $p<0.01$, $\eta^2=0.12$), confirming it can classify as a quiet eye. The quiet eye duration and onset timing were reported.

Integrated neck and eye deviations. A non-significant trend was drawn by Natrup et al. (2021) regarding the maximal neck angles indicating that differences might exist in neck kinematics between expertise levels. In an attempt to identify these differences more clearly, another metric was chosen: the integrated neck angle deviation ($\mathcal{A}$). It was computed by integrating the neck and eye angles over the duration of the acrobatics as follows:

$$\mathcal{A} = \int_0^1 \sqrt{\theta^2 + \phi^2}\, d\tau \tag{2}$$

where τ is the time normalized over the duration of the acrobatics, θ is the elevation and ϕ is the azimuthal angle formed by the eye or neck joint.

This metric was chosen as it considers the joint angular displacement during the whole acrobatics in contrast with the maximum value considering only the peak. This metric increases as more time is spent further away from the resting position.

Anticipatory and compensatory movements. As it was shown in gymnastics that the body, neck, and eye movements were correlated during acrobatics (Von Laßberg et al., 2014), we analyzed the neck and eye angles time series in combination to identify specific sequences of the visuomotor behavior. During *anticipatory* movements, the neck and eyes rotate synergistically in the same direction with the common goal of reorienting the gaze. During *compensatory* movements, the eyes rotate in the opposite direction to compensate for the neck rotation. These strategies were numerically characterized by periods of at least 40 ms where the head and eye movements were either parallel (anticipatory) or anti-parallel (compensatory) with a tolerance of 20° (Fig. 3).

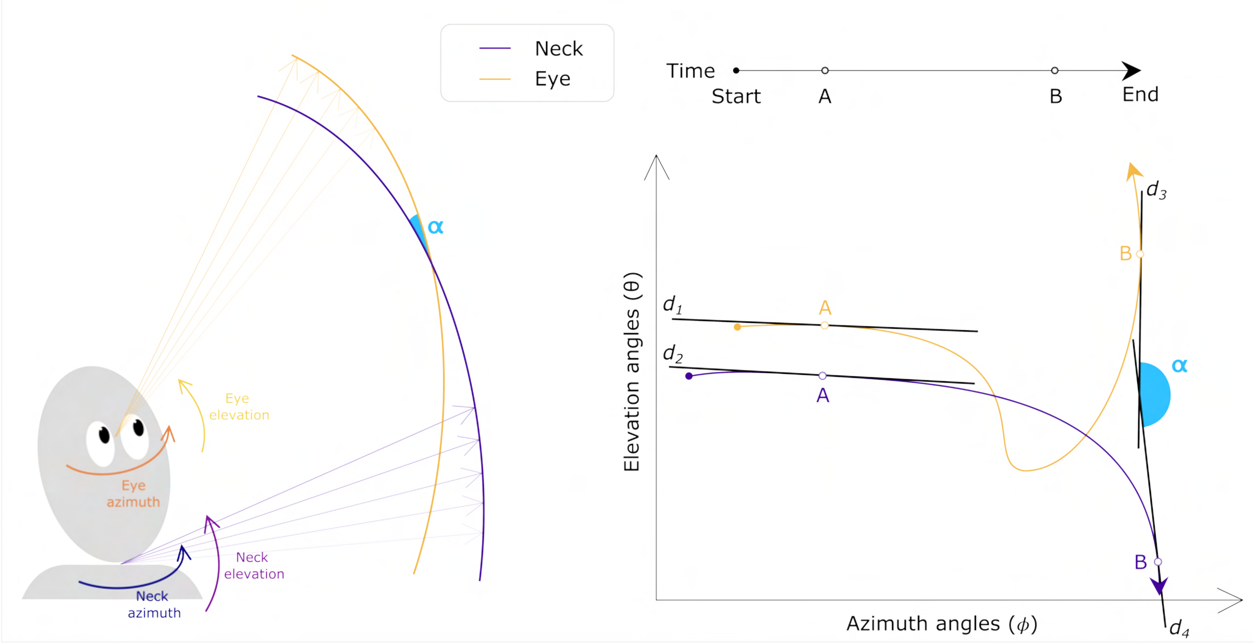


Figure 3. Definition of the eye and neck angles (left) and illustration of the numerical identification of anticipatory/compensatory movements, according to angle-angle plots (right). When the eyes and neck are moving in the same direction in an anticipatory movement, the angle α is small ($-20° < \alpha < 20°$ on the left figure). Anticipatory/compensatory movements are numerically identified when the tangents d_i of the neck and eye angles are aligned. At instant A, the neck and eye movements are almost parallel ($d_1 \mathbin{/\!/} d_2$), meaning that an anticipatory movement would be detected if it persisted for more than 40 ms. At instant B, the neck and eye movements are almost anti-parallel ($d_3 \mathbin{/\!/} -d_4$); if the angle α is large enough ($180 - 20° < \alpha < 180 + 20°$), a compensatory movement would be detected.

Spotting is characterized by a neck rotation aiming to slow down the head rotation under $120°/s$ in the gymnasium reference frame (Davlin et al., 2004).

Self-motion detection is a newly proposed task-specific strategy to describe a behavior where the eyes are kept still in the head reference frame even though the head is rotating in the gymnasium reference frame. *Self-motion detection* is defined in analogy to gaze anchoring, which was previously observed in multiple sports (see review Vater et al., 2020b, for details). Gaze anchoring is a covert attention strategy involving stabilization of the gaze on an optimal position in the environment to track objects/players' movements in the peripheral vision. On the other hand, self-motion detection refers to a new covert attention strategy involving stabilization of the gaze in the head reference frame. It was shown in other sports, that eye movements deteriorated the detection of moving objects in the peripheral vision (Vater et al., 2020a). Hence, fixing the eye orientation relative to the head would increase the ability to perceive the apparent movements from the environment caused by the athlete's own movements in space, especially in acrobatic sports such as trampolining. During self-motion detection, the image on the retina might move too rapidly to achieve foveal acuity. Thus, it is suggested that athletes would rely instead on their peripheral vision to detect movements, allowing for the identification of their rotation velocity.

Self-motion detection sequences were identified when the angular velocity of the eyes in the head reference frame was smaller than $100^{\circ}/s$ for at least 40 ms, except when spotting was simultaneously detected. The velocity threshold of $100^{\circ}/s$ was chosen in analogy to the threshold generally accepted for fixation detection using the velocity-based approach in fixed-head experiments (see review Punde and Manza, 2016, for details).

2.7 Statistical analysis

2.7.1 0D metrics

2.7.1.1 Typical metrics

To evaluate the effect of expertise on visuomotor behavior, six metrics extracted from the temporal evolution of the eye movements and body kinematics were compared: the duration and the number of tracking fixations, the duration and onset of the quiet eye period, and the integrated neck and eye deviations. Due to the uneven number of repetitions between athletes, the median value of each metric for each athlete was retained for statistical analysis. A mixed ANOVA was used with *Expertise* (sub-elite, elite) as an inter-subject and the *Acrobatics* ($Acro_{back}^{0\ twist}$, $Acro_{front}^{{}^1/_2\ twist}$, $Acro_{back}^{1\ twist}$, $Acro_{front}^{1{}^1/_2\ twist}$) as an intra-subject factor. A Greenhouse-Geisser correction was applied when Mauchly's sphericity test detected significant differences between the variances. The F-value (F), p-value (p), and eta squared (η^2) values from the mixed ANOVA were reported. Due to the small sample size, a sensitivity analysis was carried out to assess the impact of the data normality hypothesis on the statistical results; the conclusions from the parametric (Student's t-test) and non-parametric (Wilcoxon or Mann-Whitney) versions of the post hoc tests were compared. The results from the parametric tests were reported when the conclusions from both types of tests were in agreement, the results from the non-parametric tests were reported otherwise. For the Student's *t*-tests, the *p*-value (*p*), *t*-test (t), and Hedge's g (g) values were reported. Mann-Whitney tests were used to evaluate the difference between the two groups of expertise for all acrobatics combined and for each acrobatic independently. The *p*-value (*p*), U-value (U), and Hedge's g (g) from the Mann-Whitney tests were reported. Wilcoxon tests were used to evaluate the difference between *Acrobatics*. The *p*-value (*p*), W-value (W), and Hedge's g (g) values from the Wilcoxon tests were reported. A Bonferroni correction was applied to the *p*-values to account for the test multiplicity during the comparison between *Acrobatics* (n=6) and the comparison between *Expertise* classes with fixed *Acrobatics* (n=4). Effect sizes were considered trivial (<0.009), small (0.01–0.059), moderate (0.06–0.139), or large (≥0.14) when using η^2 (Miles and Shevlin, 2001) and trivial (<0.20), small (0.20–0.49), moderate (0.50–0.79), or large (≥0.80) when using Hedge's g (Cohen, 2013). All statistical analyses were done with the Pingouin Python toolbox with the significant threshold fixed at $p<0.05$ (Vallat, 2018).

2.7.1.2 Exploratory metrics

Exploratory analyses were also used to describe in more detail the differences in visual strategies used by the two groups of trampolinists and were considered relevant to advance the knowledge in this field.

Scan path. The dwell times on each AOI and the ellipse minor and major axis lengths were also compared with the above-mentioned mixed ANOVA procedure.

Specific neck and eye strategies. The proportion of the acrobatic when athletes exhibited the specific strategies, namely anticipatory, compensatory, spotting, and self-motion detection, were reported. The proportions were compared with the above-mentioned mixed ANOVA procedure.

2.7.2 1D metrics

2.7.2.1 Exploratory metrics

Specific neck and eye strategies. The relative timing during acrobatics when the specific strategies were used by athletes was reported. Over the duration of the acrobatics, when a specific strategy was present, it was attributed the value 1 (0 otherwise), resulting in a step curve representing the temporal appearance of the specific strategies. The step curves were compared between groups of expertise with 1D statistical parametric mapping (SPM1D) (Pataky, 2012). Note that although this metric is not directly measured, it still preserves the temporality of events (1D metric).

SPGO. To identify differences in the temporal evolution of SPGOs, they were unfolded to obtain a flat surface (see the top of Fig. 10 for a visual representation of the unfolding). One unfolded SPGO was chosen as representative of the athlete's technique: the trial with the smallest root mean square difference (RMSD) with all the other trials (one trial was chosen per athlete per acrobatics). To maintain the temporality of events, the representative SPGOs were compared between the two groups using SPM1D in x- and y-axes. To assess the inter-athlete variability, the norm of the standard deviation (STD) between the representative unfolded SPGOs was measured for each instant of the acrobatics. This STD was averaged over the duration of the unfolded SPGOs to obtain the mean standard deviation (MSTD). To assess the intra-athlete variability, the MSTD was measured between each trial.

This study focuses on the visuomotor differences between expertise levels that are generalizable across acrobatics. Hence, the differences between acrobatics will be roughly presented, but are considered outside of the scope of this article.

3 Results

For conciseness, only a summary of the significant results is presented in the text (see Tab. 2 for all results from the mixed ANOVAs).

Number of fixations. There was a small main effect of the factor *Expertise* on the number of fixations (F[1,15]=5.49, p=0.033, η^2=0.047); elite athletes had a greater number of fixations than sub-elite athletes (t=2.35, p=0.033, g=1.08[large]) (Fig. 4).

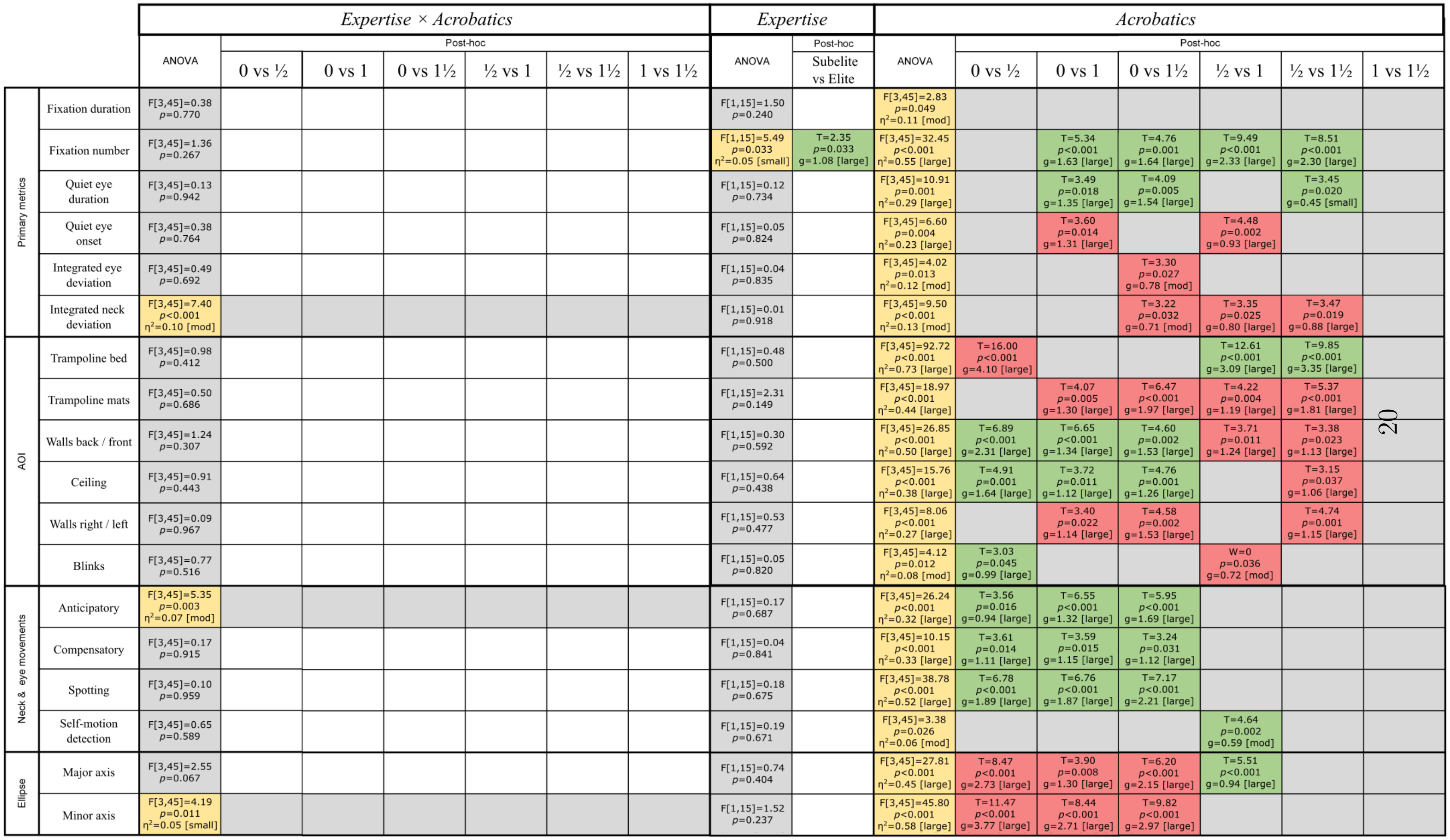
Integrated neck deviation. The mixed ANOVA revealed a moderate effect of the interaction *Expertise* × *Acrobatics* (F[1,15]=7.40, $p<0.001$, η^2=0.10) on the integrated neck deviation, but no effect of the factor *Expertise* was revealed for each acrobatic independently.

Ellipse minor axis. There was a small effect of the interaction *Expertise* × *Acrobatics* on the ellipse minor axis length (F[3,45]=4.19, p=0.011, η^2=0.05), but the Bonferroni corrected post hoc analysis did not reveal any effect of the factor *Expertise* for each acrobatic independently (Fig. 6).

Anticipatory neck and eye movements. There was a moderate effect of the interaction *Expertise* × *Acrobatics* on the time spent doing anticipatory neck and eye movements (F[3,45]=5.35, p=0.003, η^2=0.07), but again the Bonferroni corrected post hoc analysis did not reveal any *Expertise* effect for each acrobatic independently (Fig. 7).

The mixed ANOVA revealed an effect of the factor *Acrobatics* on all metrics, but since the current study aims to highlight the differences between groups rather than between acrobatics, these results will only be presented in Tab. 2 and glanced over in Sec. 4.2.

Table 2. Results from the mixed ANOVAs are colored in yellow if significant and grey otherwise. The results from the post hocs are presented in green if the metric is significantly greater for the first acrobatics compared to the second, in red if the metric is significantly smaller for the first acrobatics compared to the second, and in grey if non-significant.



		Expertise × Acrobatics							*Expertise*		*Acrobatics*						
		ANOVA	Post-hoc						ANOVA	Post-hoc	ANOVA	Post-hoc					
			0 vs ½	0 vs 1	0 vs 1½	½ vs 1	½ vs 1½	1 vs 1½		Subelite vs Elite		0 vs ½	0 vs 1	0 vs 1½	½ vs 1	½ vs 1½	1 vs 1½
Primary metrics	Fixation duration	F[3,45]=0.38 p=0.770							F[1,15]=1.50 p=0.240		F[3,45]=2.83 p=0.049 η^2=0.11 [mod]						
	Fixation number	F[3,45]=1.36 p=0.267							F[1,15]=5.49 p=0.033 η^2=0.05 [small]	T=2.35 p=0.033 g=1.08 [large]	F[3,45]=32.45 p<0.001 η^2=0.55 [large]		T=5.34 p<0.001 g=1.63 [large]	T=4.76 p=0.001 g=1.64 [large]	T=9.49 p<0.001 g=2.33 [large]	T=8.51 p<0.001 g=2.30 [large]	
	Quiet eye duration	F[3,45]=0.13 p=0.942							F[1,15]=0.12 p=0.734		F[3,45]=10.91 p=0.001 η^2=0.29 [large]		T=3.49 p=0.018 g=1.35 [large]	T=4.09 p=0.005 g=1.54 [large]		T=3.45 p=0.020 g=0.45 [small]	
	Quiet eye onset	F[3,45]=0.38 p=0.764							F[1,15]=0.05 p=0.824		F[3,45]=6.60 p=0.004 η^2=0.23 [large]		T=3.60 p=0.014 g=1.31 [large]		T=4.48 p=0.002 g=0.93 [large]		
	Integrated eye deviation	F[3,45]=0.49 p=0.692							F[1,15]=0.04 p=0.835		F[3,45]=4.02 p=0.013 η^2=0.12 [mod]			T=3.30 p=0.027 g=0.78 [mod]			
	Integrated neck deviation	F[3,45]=7.40 p<0.001 η^2=0.10 [mod]							F[1,15]=0.01 p=0.918		F[3,45]=9.50 p<0.001 η^2=0.13 [mod]			T=3.22 p=0.032 g=0.71 [mod]	T=3.35 p=0.025 g=0.80 [large]	T=3.47 p=0.019 g=0.88 [large]	
AOI	Trampoline bed	F[3,45]=0.98 p=0.412							F[1,15]=0.48 p=0.500		F[3,45]=92.72 p<0.001 η^2=0.73 [large]	T=16.00 p<0.001 g=4.10 [large]			T=12.61 p<0.001 g=3.09 [large]	T=9.85 p<0.001 g=3.35 [large]	
	Trampoline mats	F[3,45]=0.50 p=0.686							F[1,15]=2.31 p=0.149		F[3,45]=18.97 p<0.001 η^2=0.44 [large]		T=4.07 p=0.005 g=1.30 [large]	T=6.47 p<0.001 g=1.97 [large]	T=4.22 p=0.004 g=1.19 [large]	T=5.37 p<0.001 g=1.81 [large]	
	Walls back / front	F[3,45]=1.24 p=0.307							F[1,15]=0.30 p=0.592		F[3,45]=26.85 p<0.001 η^2=0.50 [large]	T=6.89 p<0.001 g=2.31 [large]	T=6.65 p<0.001 g=1.34 [large]	T=4.60 p=0.002 g=1.53 [large]	T=3.71 p=0.011 g=1.24 [large]	T=3.38 p=0.023 g=1.13 [large]	
	Ceiling	F[3,45]=0.91 p=0.443							F[1,15]=0.64 p=0.438		F[3,45]=15.76 p<0.001 η^2=0.38 [large]	T=4.91 p=0.001 g=1.64 [large]	T=3.72 p=0.011 g=1.12 [large]	T=4.76 p=0.001 g=1.26 [large]		T=3.15 p=0.037 g=1.06 [large]	
	Walls right / left	F[3,45]=0.09 p=0.967							F[1,15]=0.53 p=0.477		F[3,45]=8.06 p<0.001 η^2=0.27 [large]		T=3.40 p=0.022 g=1.14 [large]	T=4.58 p=0.002 g=1.53 [large]		T=4.74 p=0.001 g=1.15 [large]	
	Blinks	F[3,45]=0.77 p=0.516							F[1,15]=0.05 p=0.820		F[3,45]=4.12 p=0.012 η^2=0.08 [mod]	T=3.03 p=0.045 g=0.99 [large]			W=0 p=0.036 g=0.72 [mod]		
Neck & eye movements	Anticipatory	F[3,45]=5.35 p=0.003 η^2=0.07 [mod]							F[1,15]=0.17 p=0.687		F[3,45]=26.24 p<0.001 η^2=0.32 [large]	T=3.56 p=0.016 g=0.94 [large]	T=6.55 p<0.001 g=1.32 [large]	T=5.95 p<0.001 g=1.69 [large]			
	Compensatory	F[3,45]=0.17 p=0.915							F[1,15]=0.04 p=0.841		F[3,45]=10.15 p<0.001 η^2=0.33 [large]	T=3.61 p=0.014 g=1.11 [large]	T=3.59 p=0.015 g=1.15 [large]	T=3.24 p=0.031 g=1.12 [large]			
	Spotting	F[3,45]=0.10 p=0.959							F[1,15]=0.18 p=0.675		F[3,45]=38.78 p<0.001 η^2=0.52 [large]	T=6.78 p<0.001 g=1.89 [large]	T=6.76 p<0.001 g=1.87 [large]	T=7.17 p<0.001 g=2.21 [large]			
	Self-motion detection	F[3,45]=0.65 p=0.589							F[1,15]=0.19 p=0.671		F[3,45]=3.38 p=0.026 η^2=0.06 [mod]				T=4.64 p=0.002 g=0.59 [mod]		
Ellipse	Major axis	F[3,45]=2.55 p=0.067							F[1,15]=0.74 p=0.404		F[3,45]=27.81 p<0.001 η^2=0.45 [large]	T=8.47 p<0.001 g=2.73 [large]	T=3.90 p=0.008 g=1.30 [large]	T=6.20 p<0.001 g=2.15 [large]	T=5.51 p<0.001 g=0.94 [large]		
	Minor axis	F[3,45]=4.19 p=0.011 η^2=0.05 [small]							F[1,15]=1.52 p=0.237		F[3,45]=45.80 p<0.001 η^2=0.58 [large]	T=11.47 p<0.001 g=3.77 [large]	T=8.44 p<0.001 g=2.71 [large]	T=9.82 p<0.001 g=2.97 [large]			

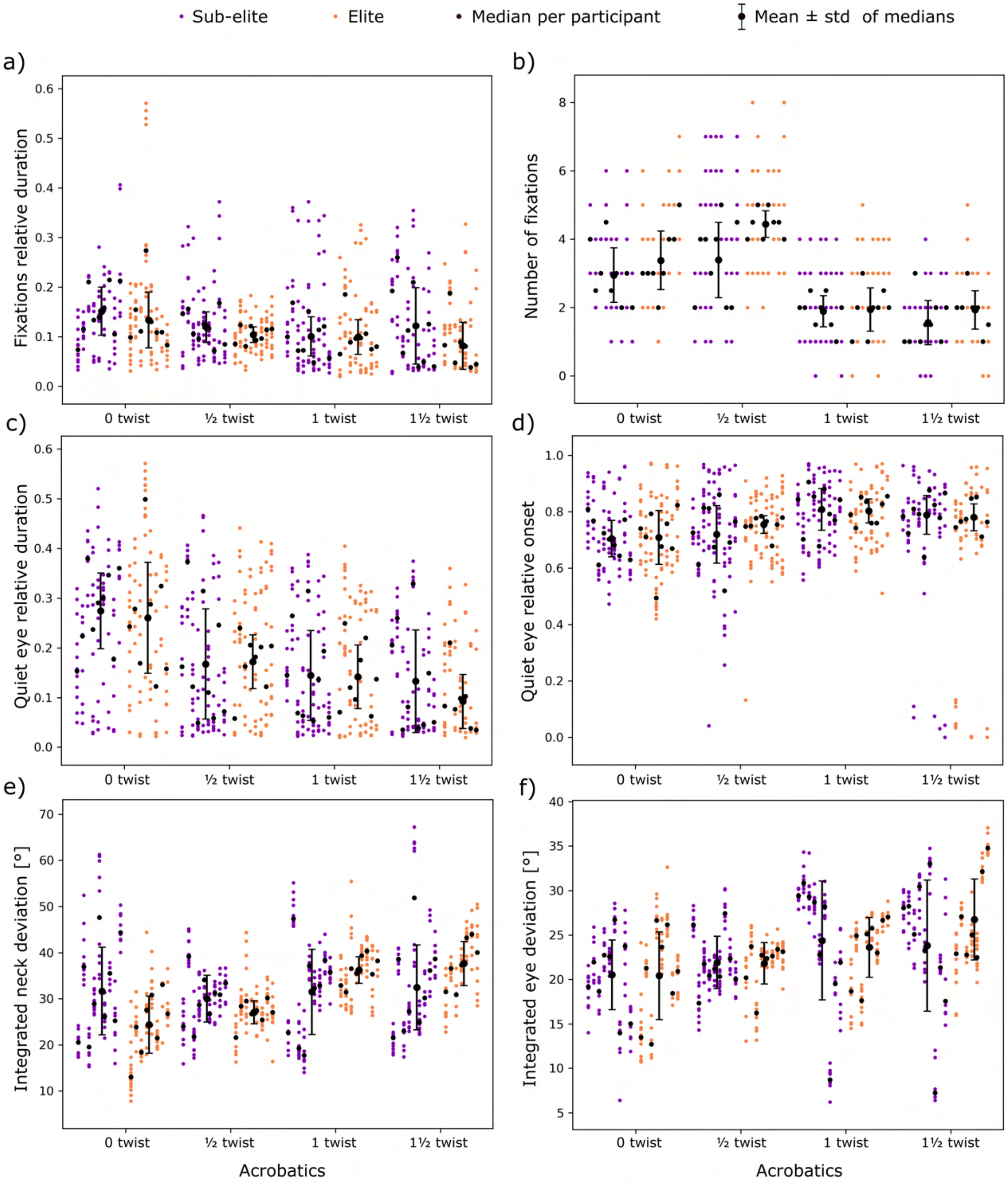


Figure 4. Distribution of the a) tracking fixation normalized duration, b) number of tracking fixations, c) quiet eye normalized duration, d) quiet eye onset, e) integrated neck deviation, and f) integrated eye deviation for sub-elite (purple) and elite (orange) athletes for four acrobatics of increasing twist complexity. The median value for each athlete (small black dot), mean of medians for each group (large black dot), and standard deviation of medians for each group (black error bar) are presented for reference.

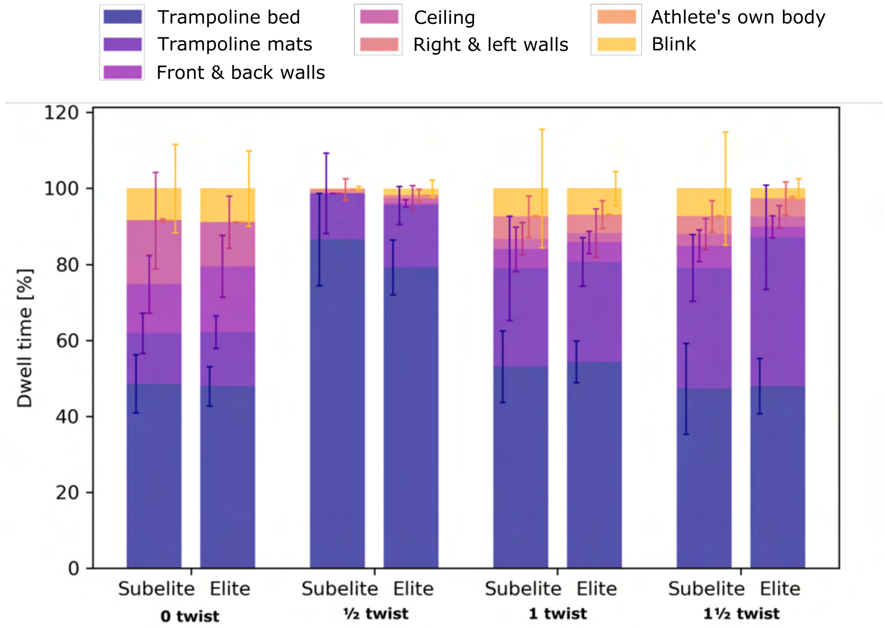


Figure 5. Mean dwell time on AOIs and mean time spent blinking for each group and each acrobatic movement. The error bars represent the standard deviation from the mean.

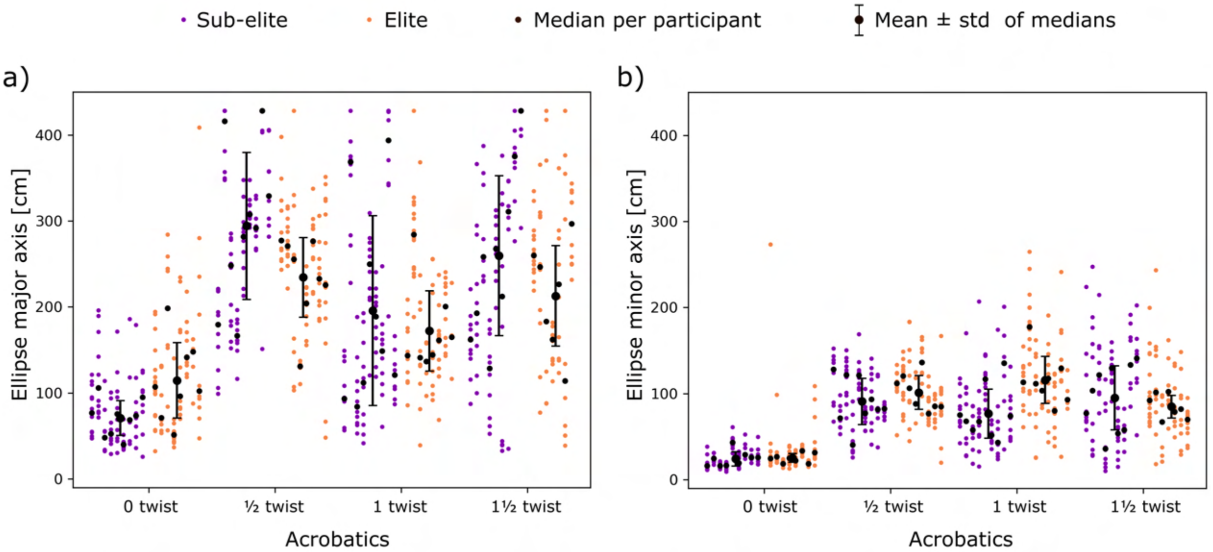


Figure 6. Distribution of the a) major and b) minor axis length of the smallest ellipse containing gaze points inside the 90^{th} percentile distance from the mean for sub-elite (purple) and elite (orange) athletes. The median values for each athlete (small black dot), mean of medians for each group (large black dot), and standard deviation of medians for each group (black error bar) are presented for reference.

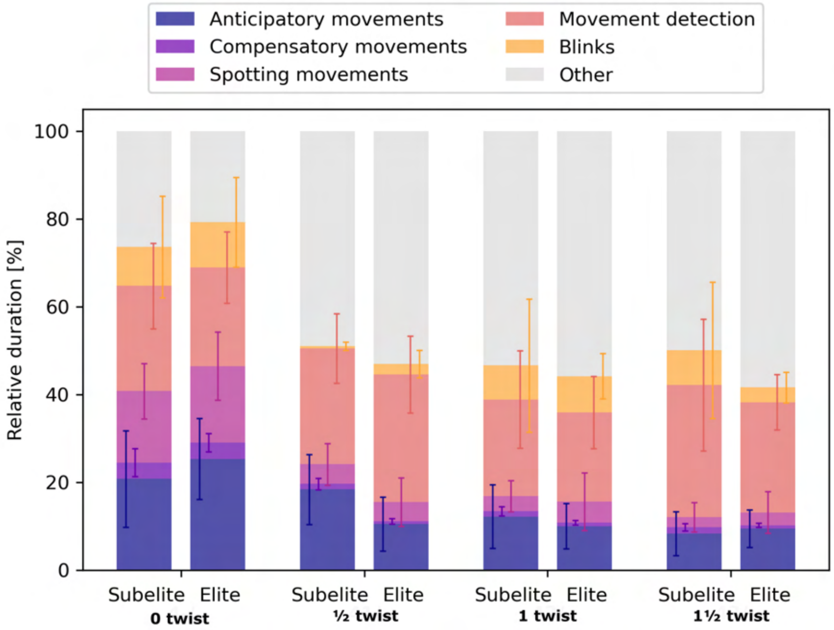


Figure 7. Mean time spent using the specific neck and eye movements and blinking. The error bars represent the standard deviation from the mean.

SPGO. The SPM1D revealed no significant differences in SPGOs between the two groups for each acrobatic independently. Athletes of both groups exhibited a large intra- and inter-athlete variability during the execution of each acrobatic (Tab. 3 and Fig. C.1 in Appendix C). The inter-athlete variability was larger than the intra-athlete variability. The inter-athlete variability was larger in the sub-elite group for all acrobatics. The intra- and inter-athlete variability was the smallest for the $Acro\,^{1/2\ twist}_{front}$.

Table 3. Mean standard deviation (MSTD) of the temporal evolution of the projected gaze orientation (SPGO) between trials (intra-athlete variability) and between athletes (inter-athlete variability).

		$Acro\,^{0\ twist}_{back}$	$Acro\,^{1/2\ twist}_{front}$	$Acro\,^{1\ twist}_{back}$	$Acro\,^{1 1/2\ twist}_{front}$
Intra	Sub-elite	1.16 ± 0.39 m	0.79 ± 0.23 m	1.38 ± 0.66 m	1.69 ± 0.76 m
	Elite	1.38 ± 0.52 m	0.90 ± 0.28 m	1.23 ± 0.39 m	1.26 ± 0.24 m
Inter	Sub-elite	2.61 m	1.60 m	2.47 m	2.77 m
	Elite	1.86 m	1.33 m	2.05 m	2.34 m

Briefly, the only significant *Expertise*-induced difference between both groups was an increased number of fixations in elites. There were significant differences between all *Acrobatics*.

4 Discussion

Our goal was to investigate the differences in visuomotor strategies between elite and sub-elite trampolinists during various acrobatics in ecological settings. We found that visuomotor behavior did not differ between the two groups except for the number of tracking fixations which was higher in elites. In addition, both groups had a similar dwell time on each AOI Fig. 5. In accordance with previous findings, trampolinists spent most of their acrobatics looking at the trampoline bed, as typically prescribed by coaches. In addition, it was confirmed that most athletes used spotting as previously reported. Interestingly, this study sheds light on a new visuomotor strategy called self-motion detection where athletes keep their eyes still during fast head rotations.

4.1 Visuomotor behavior comparison between elite and sub-elite trampolinists

Bardy and Laurent (1998) showed that elite gymnasts can better translate the available visual information into appropriate kinematic adjustments reducing landing imbalance. Thus, we initially hypothesized that elites would demonstrate superior visuomotor strategies over sub-elites when assessing their eye movements combined with their body kinematics. However, our results only weakly support this assumption with only a significant difference found between expertise levels for one out of six metrics: a larger number of fixations were observed in elites. Since the fixation relative duration was similar between the two groups and elite athletes did more fixations, elite athletes spent a larger portion of their acrobatics fixating. This result is in agreement with a previous study (Heinen, 2011) in which expert gymnasts spent a larger portion of their flight time fixating on the environment compared to novices during a backward somersault on a trampoline. The smaller time spent doing fixations might be explained by sub-elite trampolinists "*losing time*" searching for an appropriate fixation target whereas elite athletes would know in advance where to fixate. Elite would be able to anticipate more precisely the eye orientation needed to reach fixation targets. The longer duration of fixations in elite athletes would also mean that fixation was prioritized over anticipatory movements, self-motion detection, blinking, and other unidentified movements (Fig. 7) highlighting the importance of fixation for spatial orientation. It should be noted that we normalized the fixation duration by the acrobatics duration and that elite athletes had a longer acrobatics duration (Fig. F.1 in appendix F), thus elite athletes also spent more absolute time doing fixations than sub-elite athletes.

Previously, Natrup et al. (2021, 2020) reported that the quiet eye onset was delayed in elite compared to sub-elite trampolinists during both back tuck somersault and back somersault with a twist. In the current study, we did not find any differences in the quiet eye onset between the two groups. The conflicting conclusions could be attributed to differences in fixation definitions and identification methods. We measured the quiet eye onset as the normalized moment when the last tracking fixation started. Conversely, in studies by Natrup et al. (2021, 2020), the normalized onset of only one fixation was reported, which we interpreted as being the last fixation before landing. In these studies, the authors manually identified this fixation when "*the gaze remains stationary on one reference point for five video frames or longer*". The gaze angle profiles were provided to help in the identification of the fixation as in a previous study by Heinen (2011). In the current study, the quiet eye duration was also reported, but since the quiet eye period extends until shortly before landing, the quiet eye onset and duration are highly correlated. However, no difference was revealed in the quiet eye duration between the two groups. Contrary to what has been found in various sports (see Lebeau et al., 2016, for a meta-analysis), where a longer quiet eye was associated with increased expertise and performance, we did not find an expertise effect on the quiet eye duration. However, these differences are often reported between expert and novice groups whereas here, we compared elite and sub-elite athletes since novices would not be able to execute twisting somersaults. As the expertise gap between the two groups decreases, the difference in visuomotor behavior might become more subtle and even disappear. We observed a trend such that as the number of twists increased, the quiet eye started later leading to a shorter quiet eye duration.

The findings from the current and previous (Natrup et al., 2021, 2020) studies point towards similar visuomotor behavior between elite and sub-elite trampolinists. The number of studies remains small, but in each study, only one among multiple metrics relating to visuomotor behavior differed between expertise groups. The inability to identify clear differences between the elite and sub-elite athletes through visuomotor strategy measurements could be attributed either to: *i)* an inappropriate choice of visuomotor metrics, *ii)* an expertise that predominantly manifests at the level of motor skills rather than perceptual-cognitive skills, or *iii)* a perceptual-cognitive expertise that cannot be captured by measuring the gaze orientation. These three possibilities are discussed in the next paragraphs.

Inappropriate choice of metrics: Klostermann and Moeinirad (2020) recommended that the gaze behavior during complex sporting movements should be studied in interaction with the temporal occurrence of sporting actions to capture the athlete-environment interaction. To conform to this recommendation and to address trampolining performance in an ecological framework, SPGOs and the temporal occurrence of specific neck and eye movements were analyzed in our study. Even though 1D analysis should be more powerful in identifying differences between groups, no difference was revealed in these metrics, meaning that the weak ability to capture differences could not be attributed to the choice of 0D metrics in this study.

Motor skill superiority: Although comparing the SPGOs did not allow for discrimination between the two groups, this metric was nonetheless informative as it revealed a large inter-athlete variability (Appendix C). This large inter-athlete variability within both groups suggests that athletes do not converge to a single most efficient strategy as they gain expertise. Instead, they may improve their own individualized strategy according to their capability. In other words, a strategy that is optimal for everyone may not exist. Moreover, the intra-athlete execution variability was also similar for both groups (Tab. 3). Thus, the motor execution errors committed by both groups should be of similar magnitude. In sports, motor execution variability is considered acceptable and even beneficial to performance as long as it is not detrimental to the objective of the task (Bartlett et al., 2007; Davids et al., 2015; Cowin et al., 2022). In trampolining, the main objective is to comply with the code of points and to land in an advantageous posture for the initiation of the next acrobatic movement. To achieve this goal, it is necessary to make feedback and feedforward kinematic corrections when the motor variability leads to unfavorable landing conditions, as previously shown in gymnastics (Bardy and Laurent, 1998). Here, trampolinists from both groups had the smallest intra-athlete execution variability during the front somersault with ½ twist (Tab. 3), the acrobatic allowing seeing the trampoline bed the longest (Fig. 5). Looking at the trampoline bed could enhance the accuracy of spatial orientation enabling making more accurate prospective corrections to the undergoing acrobatics. Perceptual strategies are presumably needed to correct for kinematic errors occurring during the execution of acrobatics intimately intertwining perception and action. Thus, the hypothesis that elite athletes only present superior motor skills without a perceptual-cognitive component is unlikely.

Perceptual-cognitive superiority: Klostermann and Moeinirad (2020) highlighted that the reported evidence on gaze behavior differences between experts and lower-skilled participants has declined over the last years, in a robust study bringing together more than 100 studies including more than 220 gaze measures from more than 2000 participants. The authors argued that perceptual-cognitive expertise would result more from enhanced perceptual skills, rather than refined gaze behaviors. In the current study, only one out of multiple visuomotor metrics revealed a behavioral difference between elite and sub-elite trampolinists. Since the visuomotor behavior appears to be similar between the two groups, it could be hypothesized that elite athletes might extract more meaningful information along the same scan path or translate the same visual information into a better motor response due to, for example, increased sport-specific knowledge acquired through practice. This can be illustrated by previous studies (Pizzera, 2015, 2012) where it was shown that gymnastics judges benefited from their own motor experience related to the task being scored to achieve better scoring results. This was further confirmed by other evidence in squash (Abernethy, 1990) and combat sports (Polzien et al., 2017), where elite and sub-elite athletes had similar gaze scan paths, while elite athletes were superior at picking up visual information along this same scan path. Thus, the limiting factor in the perceptual performance of sub-elites appears to be more related to the capability to extract and use the available information rather than the capacity to orient their gaze at appropriate locations. Due to methodological limitations and trampolining constraints (safety, invasiveness, and quick acrobatic execution), it is presently difficult to ecologically assess perceptual-cognitive skills in experts.

In summary, elite and sub-elite athletes used similar visuomotor strategies in this study, even when comparing 1D metrics, which are believed to be more representative of the actual visuomotor behavior. Although they did not help highlight expertise differences, these temporal analyses of the visuomotor behavior of trampolinists can be more easily interpreted by coaches and athletes.

4.2 Visuomotor behavior comparison between acrobatics

It was previously shown that visuomotor strategies are task-dependant (Barreto et al., 2021; de Carvalho Barreto et al., 2020). Our results are in agreement: the ANOVAs revealed significant differences between all four *Acrobatics* studied. When comparing $Acro\ ^{0\ twist}_{back}$ and $Acro\ ^{1/2\ twist}_{front}$, no significant differences were found on any of the typical metrics, whereas differences were found on all exploratory metrics showing the relevance of these non-typical metrics for more subtle differences. For the two hardest acrobatics ($Acro\ ^{1\ twist}_{back}$ and $Acro\ ^{1\,1/2\ twist}_{front}$), even the non-typical metrics could not identify meaningful differences between them, showing their similitude. The $Acro\ ^{0\ twist}_{back}$ being the only acrobatics without twist, it stands out from the others on all the metrics studied (Tab. 2). During the execution of $Acro\ ^{0\ twist}_{back}$, athletes could spend significantly more time doing anticipatory, compensatory, and spotting strategies, probably because it is an easier acrobatic from an internal representation perspective. Athletes also demonstrated a significantly denser scan path (ellipses with smaller minor and major axes) during the $Acro\ ^{0\ twist}_{back}$ suggesting that the valuable information extracted by looking at the trampoline bed was obtained mainly during the quiet eye. During the $Acro\ ^{1/2\ twist}_{front}$, the athletes are facing the trampoline for almost the entire acrobatics which allowed them to spend significantly more time looking at the trampoline bed (longer dwell time on the trampoline bed) than during the other acrobatics.

4.3 Visuomotor strategies during twisting somersaults

For the first time, we showed that athletes of both groups of expertise used specific neck and eye strategies in the same chronological order across single somersaults with 0 to $1^{1}/_{2}$ twists (Fig. 8). The fact that these strategies were common among athletes of different expertise levels indicates their relevance for the successful execution of acrobatics. The visuomotor strategies used by athletes during straight twisting somersaults are summarized in Fig. 9 and presented in chronological order in the following paragraphs.

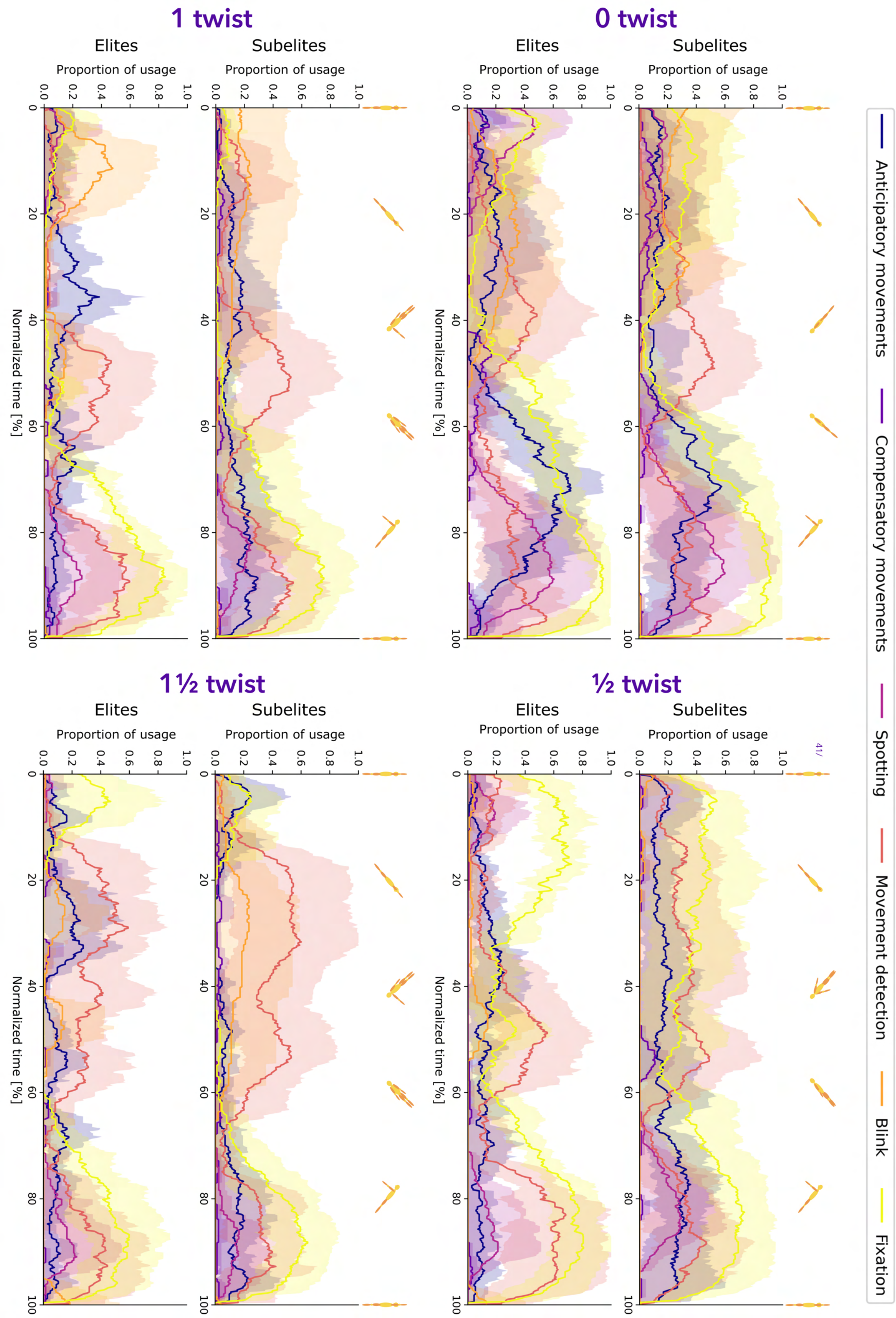
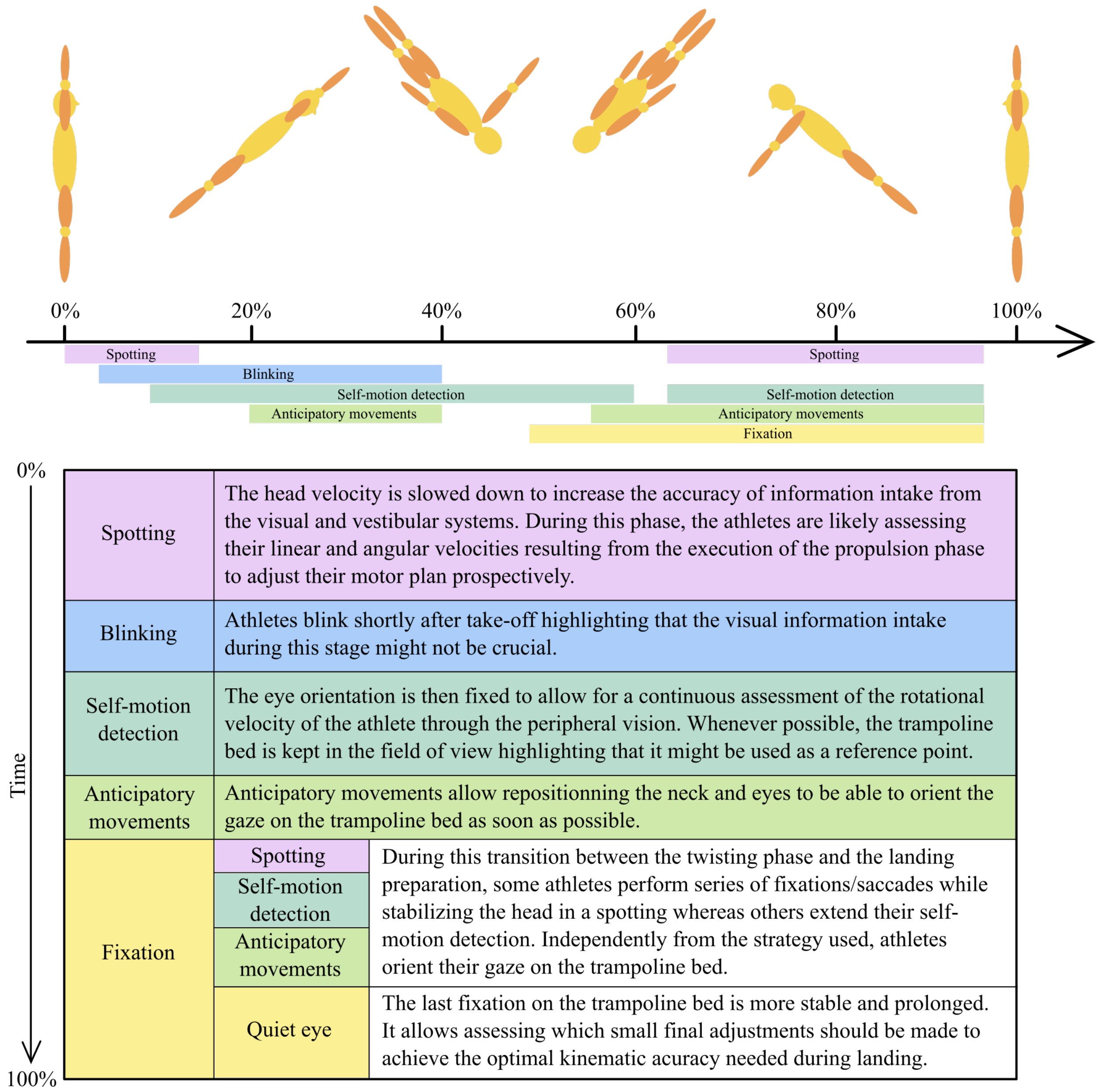


Figure 8. Mean proportion of the time athletes spent exhibiting the different types of specific head and eye strategies during four acrobatics of increasing twist rotation



Spotting		The head velocity is slowed down to increase the accuracy of information intake from the visual and vestibular systems. During this phase, the athletes are likely assessing their linear and angular velocities resulting from the execution of the propulsion phase to adjust their motor plan prospectively.
Blinking		Athletes blink shortly after take-off highlighting that the visual information intake during this stage might not be crucial.
Self-motion detection		The eye orientation is then fixed to allow for a continuous assessment of the rotational velocity of the athlete through the peripheral vision. Whenever possible, the trampoline bed is kept in the field of view highlighting that it might be used as a reference point.
Anticipatory movements		Anticipatory movements allow repositionning the neck and eyes to be able to orient the gaze on the trampoline bed as soon as possible.
Fixation	Spotting Self-motion detection Anticipatory movements	During this transition between the twisting phase and the landing preparation, some athletes perform series of fixations/saccades while stabilizing the head in a spotting whereas others extend their self-motion detection. Independently from the strategy used, athletes orient their gaze on the trampoline bed.
	Quiet eye	The last fixation on the trampoline bed is more stable and prolonged. It allows assessing which small final adjustments should be made to achieve the optimal kinematic acuracy needed during landing.

Figure 9. The sequence of strategies typically used by athletes during single somersaults including 0 to $1^1/_2$ twists. The strategies are arranged in chronological order on the timeline, along with an estimate of when they usually occur during the acrobatics. The potential role of each strategy is outlined in the table.

4.3.1 Spotting

Our results reinforce that athletes use two spotting sequences, namely, shortly after take-off and before landing (Sanders, 1994). The second spotting was used in preparation for the upcoming landing to facilitate the gaze fixation on the trampoline bed. As the head slows down in the gymnasium reference frame, the eyes need to compensate for a smaller angular velocity, thus it becomes easier to stabilize the gaze endpoint in the gymnasium (Takahashi et al., 1989). The spotting sequence at the end of the acrobatics was longer and present in most athletes (Fig. 8). The function of spotting behavior might be larger than solely increasing foveal vision acuity. Indeed, it was observed that gymnasts still used spotting behavior in no vision condition during a backward somersault (Davlin et al., 2004). Spotting could also increase the accuracy of the vestibular functions as slowing down the head movement increases the precision of the angular and linear velocities estimated by the vestibular system (Kingma and Van de Berg, 2016). Taking advantage of this increased vestibular accuracy, some athletes, mainly elites, used a short spotting sequence at the beginning of their acrobatics. The occurrence of this spotting sequence at the beginning decreased as the acrobatics difficulty increased since less time was available due to the increased time spent twisting.

4.3.2 Blinks

It was previously observed (Heinen, 2011) in female gymnasts performing back tuck somersaults on a trampoline that sub-elite athletes blinked during their acrobatics, whereas elite did not. Conversely, we observed that both elite and sub-elite trampolinists blinked during their acrobatics (Fig. 5). This disagreement likely comes from the sports background of the participants. In gymnastics, there is a shorter aerial phase (approx. 0.8 s) compared to trampoline (approx. 1.8 s). Hence, gymnasts might be discouraged from blinking as they have less time to execute their acrobatics. The blinking behavior may be indicative of sports rather than expertise adaptations. Therefore, caution must be exercised when extrapolating the results from one acrobatic sport to another.

Gaze shifts exceeding 33° are prone to be accompanied by a blink (Evinger et al., 1994). After take-off, athletes generally used large gaze shifts to reposition their gaze in an anticipatory movement, which was often coupled with a blink. Blinks mainly occurred in the first 60% of the acrobatics to avoid interference with the landing preparation. The visual information available during the first part of the acrobatics would not be crucial, especially during backward somersaults (with 0 or 1 twist), in which the athlete is not facing the trampoline.

4.3.3 Anticipatory movements

Anticipatory movements result from combined movements of the neck and eyes to rotate the gaze in the athlete's reference frame. These movements can fulfill two purposes: counteracting the body rotation to achieve visual fixations or repositioning the gaze (*i.e.*, gaze shifts). Anticipatory movements occurred after take-off (20-40%) to reposition the gaze. As these quick gaze shifts have the same function as saccades, it can be assumed that they suppress the visual information whether they were accompanied by a blink or not. Athletes also used synergetic eye-neck movements to stabilize the gaze endpoint in the gymnasium reference frame mainly at the end of the acrobatics. Athletes were able to stabilize their gaze during almost the whole duration of the front somersault with ½ twist due to its special geometry allowing facing the trampoline bed.

We observed that anticipatory movements were often initiated with eye-only movements, followed by the synergetic movements of the neck and eyes in the same direction. This delayed neck onset is in agreement with what was observed in gaze shifts (Guitton and Volle, 1987) and smooth pursuit (Lanman et al., 1978). It may be due to the head's higher inertia compared to the eyes (Zangemeister et al., 1981). We did not characterize the eye-only movement preceding the anticipatory movement, it fell inside the category "other" (Fig. 7) leading to a possible underestimation of anticipatory movement proportion. This initiation delay accounts only for a portion of the "other" category meaning that we could not identify the function of all neck-eye movements. Hence, this study increases our understanding of the visuomotor strategies used by trampolinists, but more studies are needed to fully understand them.

4.3.4 Self-motions detection

Von Laßberg et al. (2014) observed that gymnasts did not stabilize their gaze on the environment during twists. Similarly, we observed that trampolinists mainly used self-motion detection while twisting. Whereas it was not possible to assess if athletes used their peripheral vision in an ecological sporting context, it was previously argued that athletes must use an optimal combination of foveal and peripheral vision to achieve their level of performance (Klostermann et al., 2020). Moreover, keeping the eyes still in the head's reference frame enhanced the accuracy of motion detection in the peripheral field of view (Vater et al., 2020a). Hence, athletes might use their peripheral vision to detect the apparent motion of the gymnasium while twisting. This detection would help athletes monitor their angular velocity in the air.

Keeping the eyes still in the head reference frame while the head is in rotation implies that the vestibulo-ocular reflex (VOR) is suppressed. Indeed, VOR should compensate for the rotation of the head with eyes rotation in the opposite direction enabling stabilization of the gaze in the environment. Gymnastics training can modify the gaze behavior of athletes by suppressing VOR during self-generated acrobatic motions (van der Veen et al., 2022; von Laßberg et al., 2020). Here, we showed that both elite and sub-elite athletes exhibited self-motion detection sequences implying that trampoline training even at a lower level induces VOR suppression. It is worth noting that self-motion detection was used by athletes with different eye orientations.

To our knowledge, self-motion detection was not previously reported in the literature. Since the visual strategies used by athletes are context-specific (Mann et al., 2007), it is not surprising that studying the gaze behavior of acrobatic athletes leads to coming across new gaze mechanisms.

4.3.5 Fixating on the trampoline bed

All athletes used the trampoline bed as a reference point before landing as previously reported by Natrup et al. (2021, 2020). Trampolinists almost only fixated their gaze on the trampoline bed and ended their acrobatics with a prolonged fixation, which we identified as the quiet eye (Fig. 10). This suggests that trampolinists needed visual information of a higher resolution (foveal focus) before landing to appropriately identify the trampoline bed pose. The trampoline bed would give them a point of reference to estimate their own spatial pose enabling them to perform adjustments to their motor plan accordingly, as shown in gymnastics (Heinen et al., 2012a).

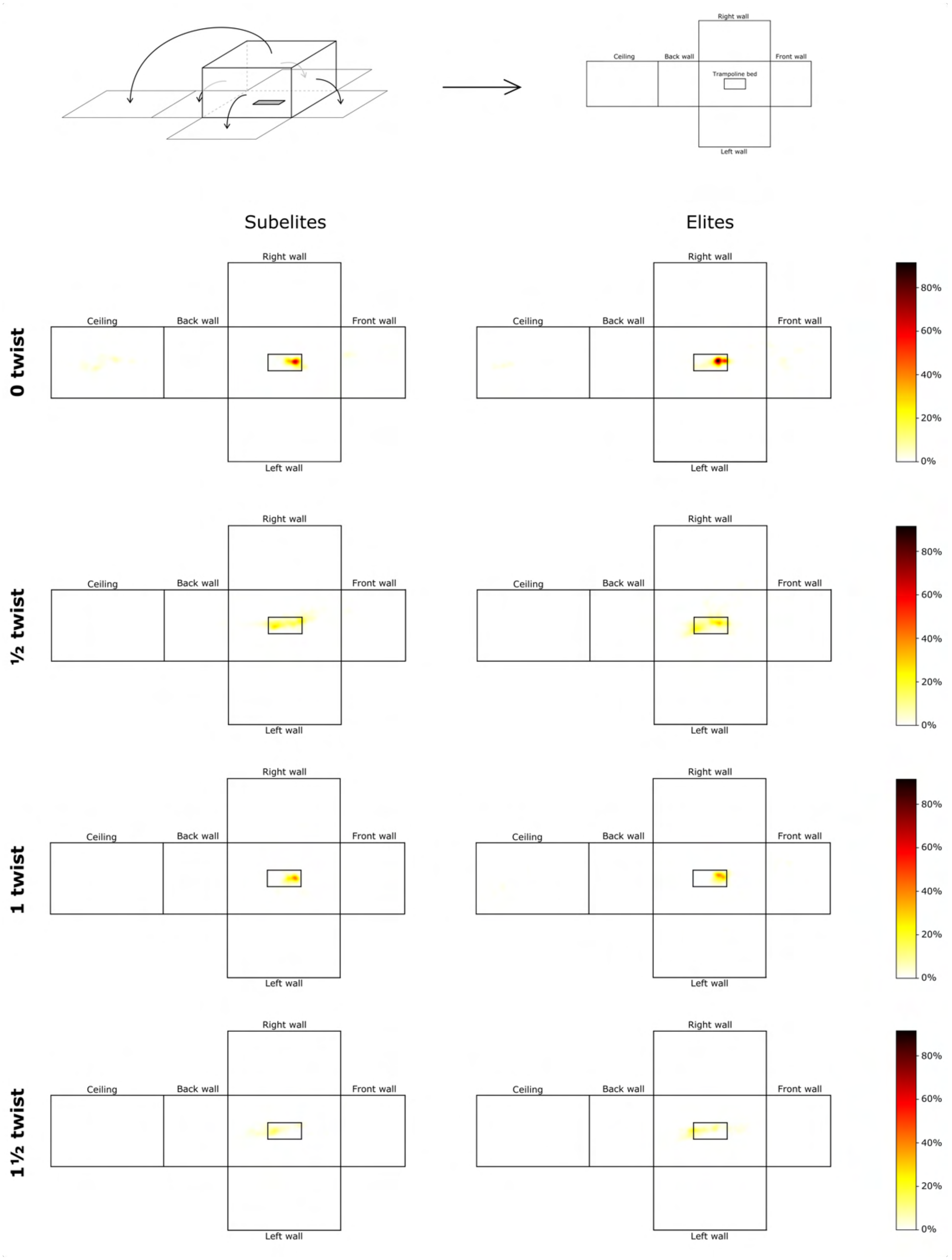


Figure 10. Fixation orientations projected on the unfolded gymnasium. The Gaussian heat map indicates the relative time spent by sub-elites (left side) and elites (right side) fixating on each region of the environment. The athletes' initial reference frame was virtually rotated so that all athletes started their acrobatics facing the front wall.

Before the onset of the quiet eye, trampolinists oriented their gaze on the trampoline. During this period, athletes used either one of the two following strategies: a series of fixations and saccades or a prolonged period of self-motion detection. This behavior was observed by inspecting the heat maps of gaze orientation on the trampoline bed (Appendix E). We observed that prolonged self-motion detection was mainly used by elites. This strategy might be preferred due to the continuous flow of information it provides. In contrast, saccades momentaneously prevent the acquisition of visual information.

4.4 Coaching implications

During the whole acrobatics, athletes spent most of their opened-eyes time orienting their eyes towards the trampoline bed (Fig. 5), which is in agreement with a usual instruction provided by coaches, namely looking at the trampoline for as long as possible. The trampoline bed is thought by coaches to be a good choice of reference point for spatial orientation since it corresponds to the landing surface and is the only invariant element in the competition environment (*i.e.*, walls and ceiling differ depending on the competition gymnasium).

Another common coach belief is that, due to the geometry (*i.e.* head and trunk orientation) of the acrobatics $Acro~^{1/2~twist}_{front}$ and $Acro~^{1~twist}_{back}$, athletes should be able to see the trampoline bed for longer than during other acrobatics. Our study has confirmed it for $Acro~^{1/2~twist}_{front}$($\sim 80\%$), but not for $Acro~^{1~twist}_{back}$ ($< 60\%$). The difference likely comes from the initiation of the acrobatics where the first backward half twist of $Acro~^{1~twist}_{back}$ prevents the athletes from seeing the trampoline bed for the first quarter somersault rotation. Since athletes cannot extract meaningful information during the first quarter of this acrobatics, coaches should refrain from giving visual instruction regarding this phase.

We also observed by visually inspecting the videos captured by the eye-tracker, that during the twisting phase of $Acro~^{1~twist}_{back}$ and $Acro~^{1 1/2~twist}_{front}$, athletes oriented their heads and eyes to keep the trampoline bed in their peripheral vision. Based on their head orientation, it would have been possible to reach the trampoline bed with their foveal spot using extreme eye angles. However, such extreme eye angles are not advantageous as they would require more time to reorient the gaze and more effort due to the exponential force-elongation relationship of the antagonist eye muscles (Quaia et al., 2009). Avoiding extreme eye angles would be in line with the minimum effort principle (Kardamakis and Moschovakis, 2009). As athletes did not judge it necessary to overcome these disadvantages, the greater acuity provided by foveal vision would not be necessary while twisting. Athletes might extract sufficient information from their peripheral vision. Therefore, we recommend instructing athletes to use covert attention to identify motion in their peripheral vision instead of instructing athletes to use extreme eye angles.

4.5 Limitations

The current study presents six noteworthy limitations.

i) The data collection was carried out from August 2021 to July 2022 during the COVID-19 pandemic, a period during which athletes might not have been able to show their best trampolining performance due to disruptions in training.

ii) There is an age gap between the two groups due to the small pool of old sub-elite and young elite athletes. Thus, it is not possible to exclude that the difference in visuomotor behavior, although very limited, that was observed could have been mainly driven by age.

iii) The measurement tools (*i.e.* IMUs and wearable eye-tracker) were retained for their easiness of utilization in an ecological context and to limit the duration of the data collection sessions to 2.5 h. However, their accuracy is lower than other measurement tools such as optoelectronic marker tracking and scleral search coil. Moreover, the reconstruction pipeline introduces an error accumulation. The total error generated by the whole reconstruction pipeline was estimated from non-reported complementary measurements. The error did not exceed 10° and did not have rapid fluctuations, which was deemed acceptable in the context of this study.

iv) The neck and eye angles were computed with respect to the athlete's resting position. This orientation was defined as the zero during the calibration of the IMUs and from the eye tracker's algorithm. It was not possible to determine if the calibrations were consistent across participants, therefore there might be an over/underestimation of the neck and eye angles for some participants. However, the calibration error was small enough to be unnoticeable when visually inspecting the gaze and body kinematics reconstructions.

v) Due to measurement limitations, the CoM horizontal translations had to be neglected.

In cases where the athletes were far off-centered, this might have affected the fixations detection.

vi) We assumed that athletes' visuomotor behavior was not affected by the gymnasium's slight asymmetries, therefore we virtually rotated the athletes' data to give them the same initial orientation for comparison purposes. The SPGO might have been slightly affected by this reorientation.

4.6 Future work

To give insights into the perception-action mechanisms responsible for the motor correction applied to compensate for execution errors, the visuomotor variability should be further explored. The relationship between perceptual-cognitive and motor performance should also be further studied in the search for more efficient strategies and a holistic approach to performance as previously suggested (Voigt et al., 2023). In addition, future studies should investigate the role of peripheral vision and the vestibular system in spatial orientation as it seems athletes need a combination of sensory information to reorient themselves. Although it was shown that acrobatic movements were impaired in non-vision condition (Davlin et al., 2004; Heinen and Veit, 2020; Rezette and Amblard, 1985; Bardy and Laurent, 1998; Davlin et al., 2001b), multiple studies also showed that modifying the visual information available during acrobatic movements only had a small effect on performance (covering one eye (Heinen and Veit, 2020; Heinen and Vinken, 2011), restraining lateral peripheral vision (Davlin et al., 2001a), using stroboscopic lights (Rezette and Amblard, 1985), removing vision for specific portions of the acrobatics (Davlin et al., 2001b) or using liquid crystal goggles (Luis and Tremblay, 2008)). Therefore, athletes would need a minimum of visual information to achieve acrobatic performance, but the low quality of visual information may be compensated for by other sensory information sources and perceptual-cognitive expertise.

5 Conclusion

By studying the trampolinists' visuomotor behavior under ecological conditions, a single difference was observed between elite and sub-elite trampolinists, namely, elite athletes used more tracking fixations. During the twisting phase of their acrobatics, athletes used a context-specific strategy referred to as *self-motion detection* where the VOR is suppressed likely to perceive movement in the peripheral vision. We observed that trampolinists from both expertise groups used a predefined sequence of sensory acquisition strategies: 1) spotting, 2) blinking/anticipatory movement, 3) self-motion detection, and 4) fixation. While athletes from both groups employed similar strategies, an important inter-athlete variability in execution was observed. Athletes adapted their visuomotor strategies according to the acrobatics performed; for instance, as the difficulty of the acrobatics increased, athletes had less time to dedicate to spotting behaviors. The assessment of the athletes' visuomotor strategies provided in this study could be useful to the athletes' support team to help give athletes more accurate instructions and improve skill development.

Author contributions

Eve Charbonneau: Conceptualization, Methodology, Software, Formal analysis, Investigation, Writing - Original Draft, Visualization, Funding acquisition. **Mickaël Begon:** Conceptualization, Resources, Writing - Review & Editing, Supervision, Funding acquisition. **Thomas Romeas:** Conceptualization, Methodology, Resources, Writing - Review & Editing, Supervision, Funding acquisition.

Declaration of Competing Interest

None.

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Appendices

A Trampoline bed scan path reconstruction method

The athlete's point-of-view videos recorded with the eye tracker were manually labeled to identify reference points along the lines and borders of the trampoline bed. A perspective transformation was used to undistort the images to retrieve the gaze position in the trampoline bed reference frame. This process was repeated for each frame of all acrobatics, allowing the generation of Gaussian (standard deviation of $\sqrt{50}$ cm) heat maps for each acrobatics (Fig. A.1).

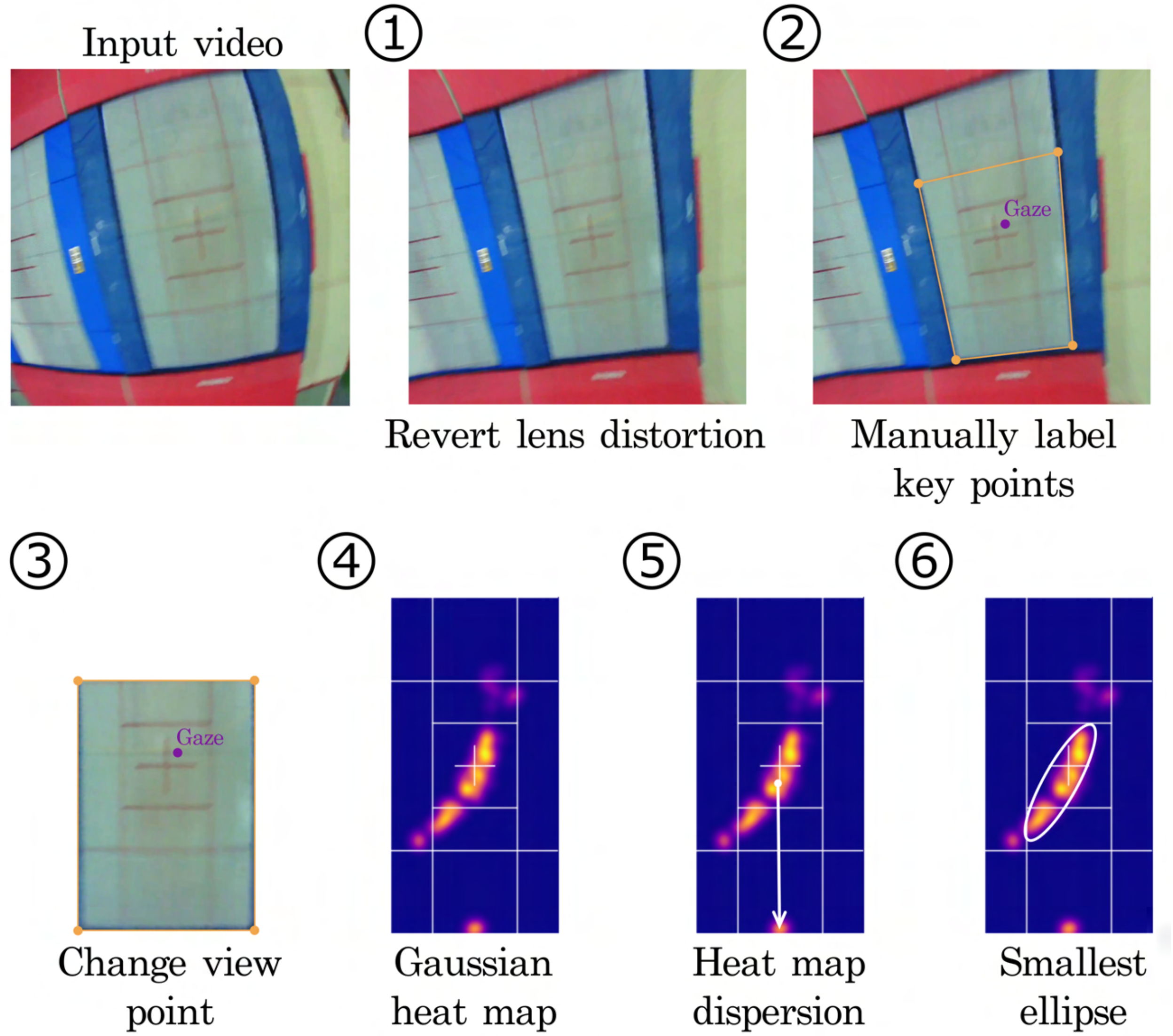


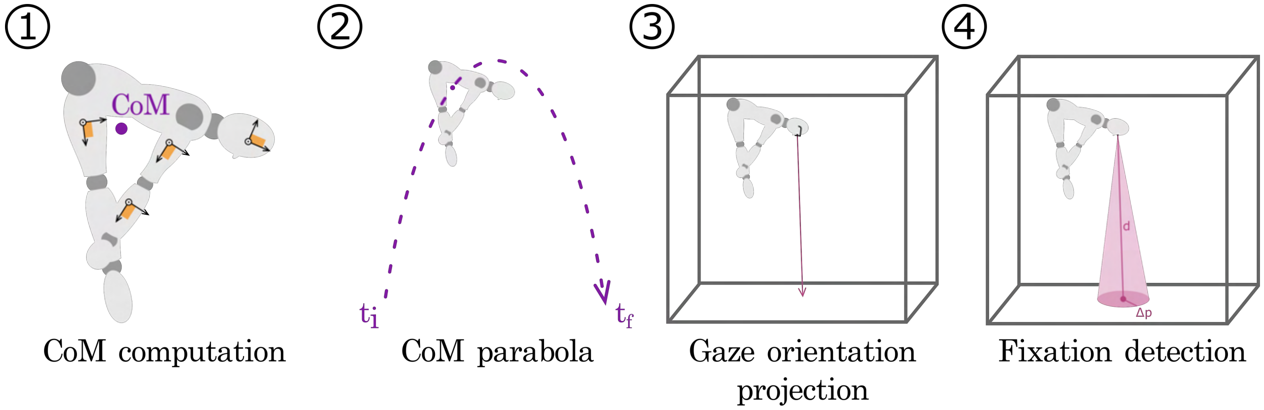
Figure A.1. Illustration of the pipeline used to identify the gaze orientation in the trampoline bed reference frame. The smallest ellipse containing all gaze orientations within the 90^{th} percentile of distance from the mean was identified for each movement.

The mean scan path position was determined by finding the mean of each gaze point in the trampoline bed reference frame. To exclude extreme values, the distance of each point from the mean was computed and the 90^{th} percentile distance from the mean was extracted. The smallest ellipse containing each point beneath the 90^{th} distance percentile was found (see supplementary materials https://osf.io/nkbps/ for an example of a fitted ellipse). The minor and major axes of these ellipses were reported.

B Projected gaze orientation reconstruction method

The segment orientations measured with the IMUs allowed for the identification of the position of the athlete's center of mass (CoM) relative to the pelvis reference frame. For each aerial phase, we assumed that the athlete's CoM followed a vertical parabolic trajectory from take-off to landing without horizontal translation. Using this method, the athlete's position and orientation in the gymnasium could be approximated. The eye angles could be joined to the body kinematics to obtain the gaze orientation in the gymnasium reference frame like in the vector-based approach suggested by Kredel et al. (2015).

To facilitate the interpretation of the temporal evolution of the gaze orientation, the gaze was projected on the gymnasium. In other words, the position where the gaze intersected with the gymnasium boundaries was reported as previously done in indoor experiments (Von Laßberg et al., 2014), outdoor experiments (Matthis et al., 2022) and in a virtual reality environment (Harris et al., 2023). In the present study, the boundaries of the environment were composed of the walls, ceiling, and trampoline. Due to the irregular shape of the gymnasium, it was assumed that the side walls were arbitrarily positioned 3 m away from the trampoline metallic frame. The temporal evolution of this intersection of the gaze with the gymnasium will be hereafter referenced as *projected gaze orientation*. The data treatment pipeline used to retrieve the projected gaze orientation is illustrated in Fig. B.1.



CoM computation CoM parabola Gaze orientation projection Fixation detection

Figure B.1. Illustration of the pipeline leading to the extraction of the projected gaze orientation.

The trampolinists initiated their acrobatics facing either the front or back wall of the gymnasium. To directly compare the temporal evolution of the projected gaze orientation between all acrobatics, the gymnasium was virtually symmetrized and the athlete's initial reference frames were rotated so that all acrobatics started in the same orientation (front wall); the data time series resulting from this process was referenced as *symmetrized gaze projected orientation* (SPGO).

C Variability of SPGO

A representative SPGO for each athlete is presented in Fig. C.1 to illustrate the large inter-athlete variability.

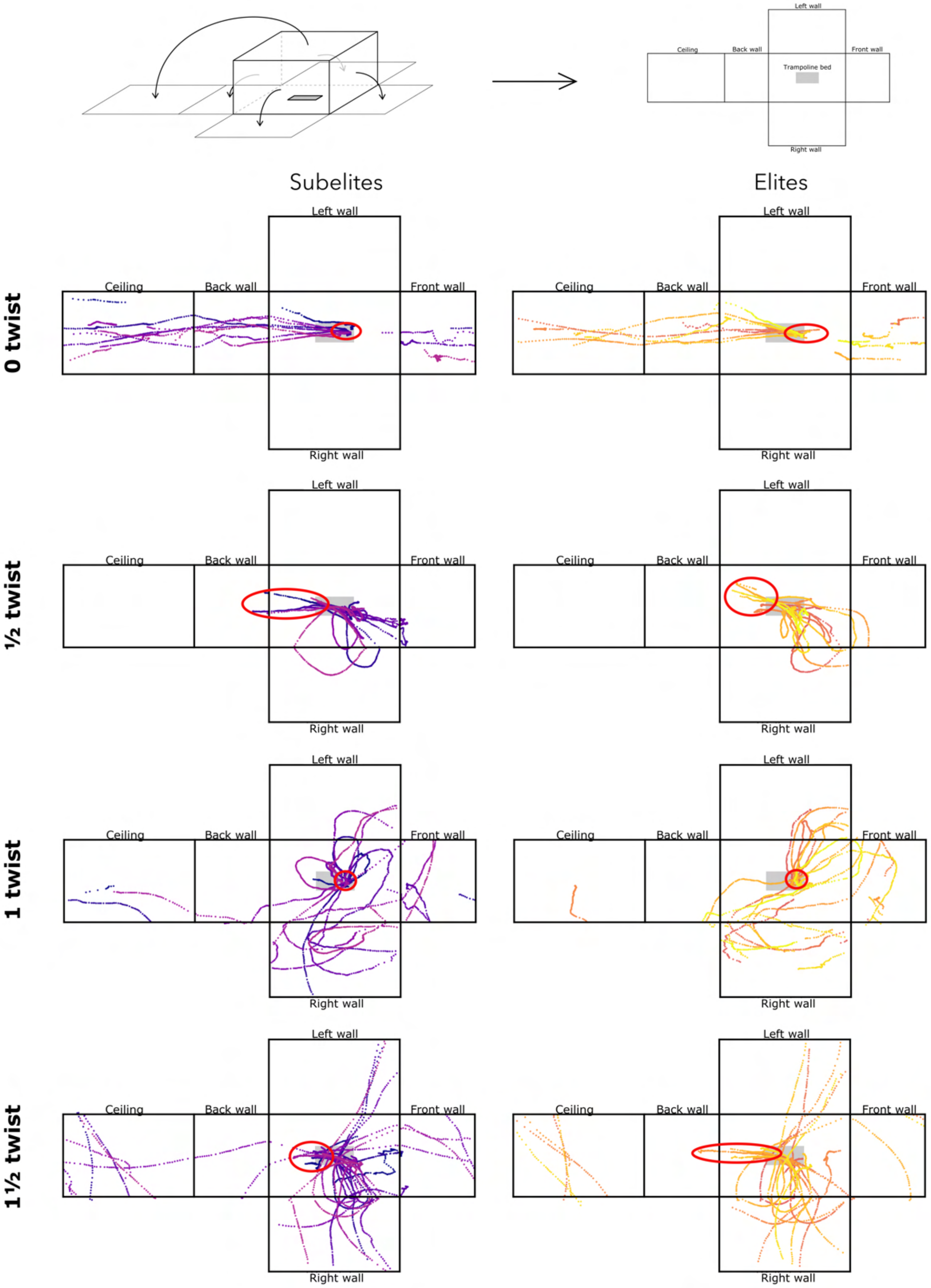


Figure C.1. One representative SPGO per athlete is depicted on the unfolded gymnasium for all sub-elites (left) and all elites (right) for the four acrobatics. Each athlete is represented with a different color. The red ellipse encloses the end (last gaze endpoint) of the SPGOs.

D Timing of specific strategies

We reported the temporal use of each specific strategy (anticipatory, compensatory, spotting, and self-motion detection). A graphical representation of the timing when athletes used the specific strategy is presented in Fig. D.1.

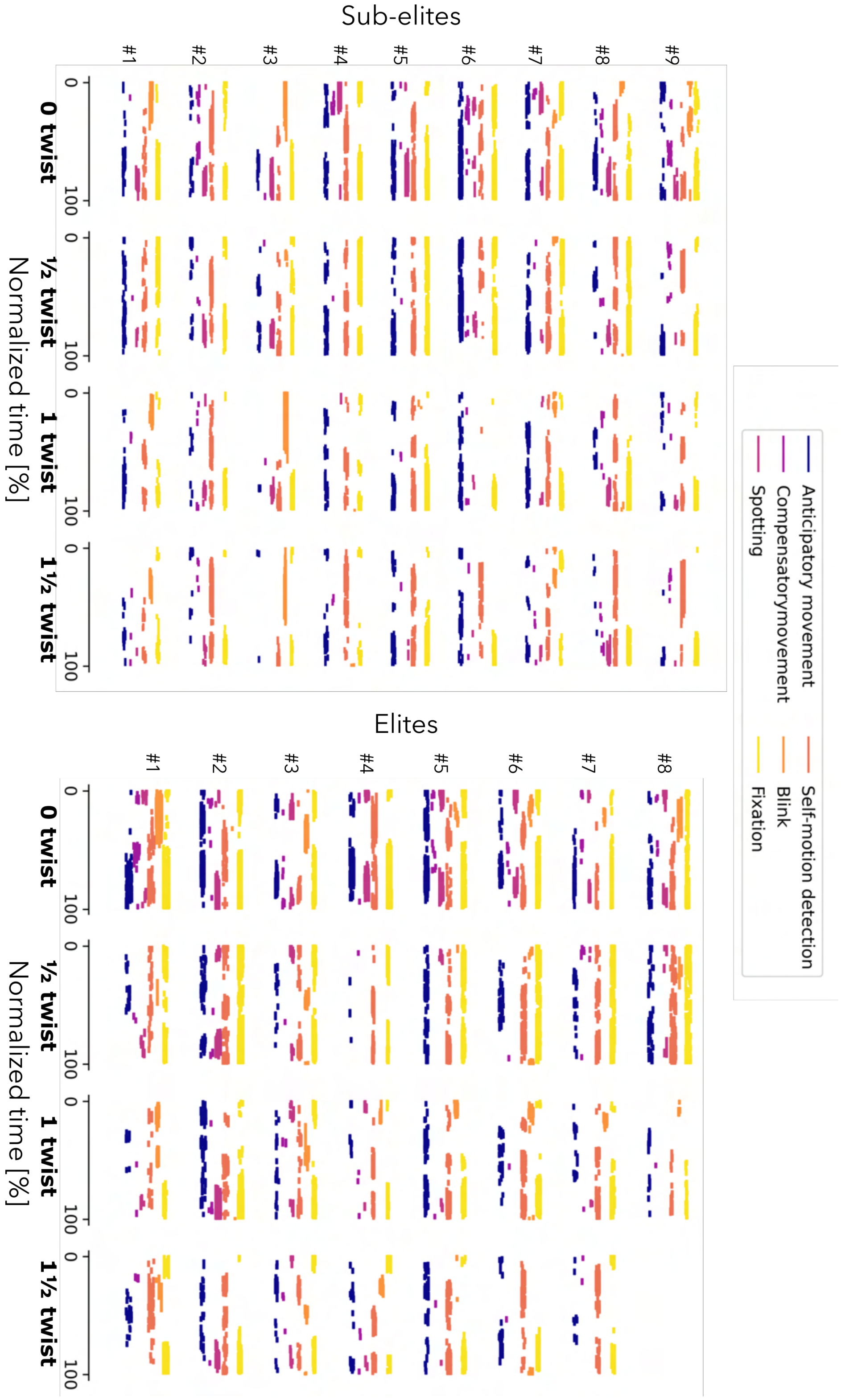


Figure D.1. Athletes' temporal usage of anticipatory (dark purple), compensatory movements (light purple), spotting (dark pink), self-motion detection (dark orange), blinks (light orange), and fixations (yellow). Each trial (sub-y-axis) from each athlete (y-axis) of each acrobatics (x-axis) is presented. The colored bars indicate that the strategy was used at this instant (sub-x-axis) of the acrobatic.

E Prolonged period of self-motion detection

Self-motion detection was characterized by little eye movement in the head reference frame while the head was in rotation in the environment. It was observed that some athletes used self-motion detection at the end of their acrobatics until the quiet eye. Fig. E.1 presents the heat maps resulting from either the use of fixation/saccade alternation or the use of self-motion detection. When athletes use a series of fixations and saccades, the gaze orientation hops from fixation to fixation where it stabilizes on specific locations on the trampoline bed. When this strategy is used, it is possible to see a series of dense spots on the heat maps representing fixation locations. On the other hand, when athletes use self-motion detection, the gaze is stabilized in the head reference frame, consequently, the gaze endpoint glides slowly on the trampoline bed. When this strategy is used, it is possible to see continuous stretched spots on the heat maps due to the rotation of the body.

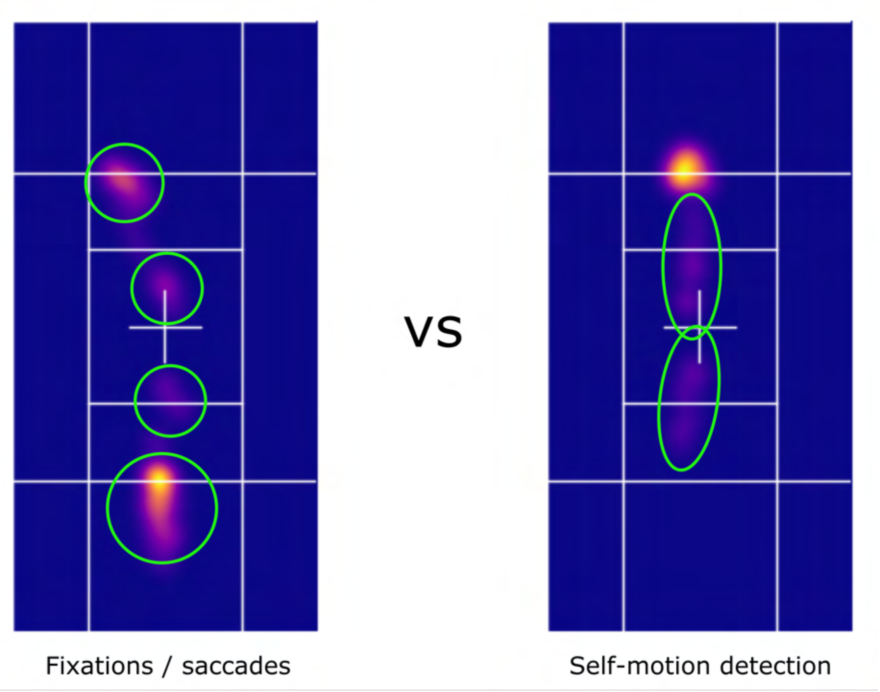


Figure E.1. Example of heat maps from one athlete using an alternation between fixations and saccades (left) and one athlete using self-motion detection (right).

F Acrobatics duration

Elite athletes performed their acrobatics higher than sub-elite athletes. It translates into a larger acrobatics duration for elites (Fig. F.1).

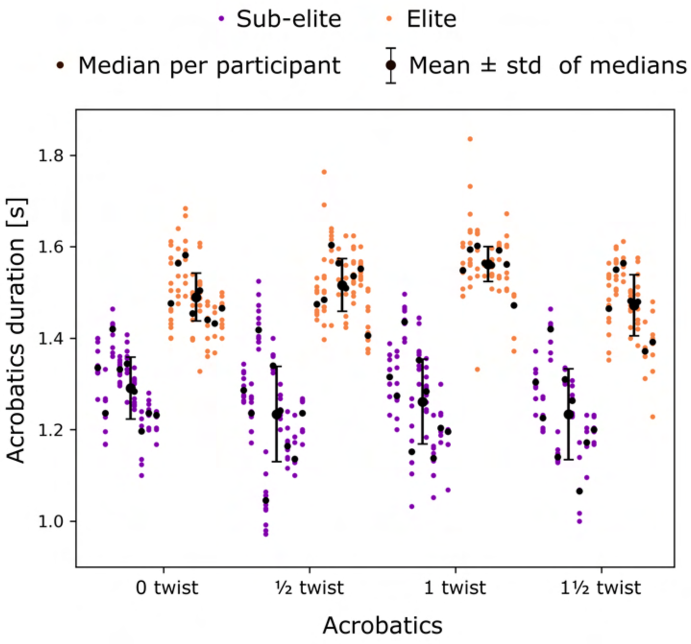


Figure F.1. Acrobatics duration for sub-elite and elite athletes.