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Does a visual reference help ballet dancers turn more successfully?

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ABSTRACT

In dance, performing multiple rotations around the longitudinal axis is a complex task that can only be accomplished proficiently by highly skilled dancers. However, this extraordinary skill has been investigated sparsely. The few studies to date have focused on the biomechanical analysis of ballet rotations. However, none have investigated the influence of visual information on continuous rotations, such as *Fouettés* or *à la Seconde* turns. Therefore, the present study aims to examine the role of a visual reference on balance control and the dance-specific head coordination – spotting – during turning performance of highly skilled ballet dancers. To this end, 12 participants performed 12 *Fouettés* (females) or *à la Seconde* turns (males) with and without a visual reference. As dependent measures, we analysed balance control (i.e., supporting foot path length), spotting duration, head isolation, and orientation (i.e., deviation of pelvis from the front). A linear mixed model was performed to analyse the influence of the visual conditions overall and over the continued performance of 12 consecutive rotations. The results revealed that overall, path length was significantly smaller in the condition without a visual reference. Spotting duration and head isolation did not differ significantly between conditions. Moreover, dancers oriented themselves better towards the front in the condition with a visual reference. When looking closer into the progression of performance over each consecutive rotation, highly skilled ballet dancers significantly decreased the supporting foot path length, and improved orientation when turning with a visual reference. On the other hand, without a visual reference, the dancers increased the spotting duration over time. Additionally, dancers increased head isolation towards the end of the turns in both conditions. These findings suggest that a visual reference helps ballet dancers sustain performance of consecutive rotations, mainly in optimising balance control and orientation. Thus, the more rotations a ballet dancer must turn, the more relevant a visual reference becomes for sustaining successful performance.

1. Introduction

Dancers are highly skilled athletes who repeatedly perform choreographed works on stage. Therefore, it is of the utmost importance for dancers to refine their skills such that their performance is consistently successful. In many dance styles – and especially in ballet – some of the most prevalent movements are rotations around the longitudinal axis. In ballet, the most common rotations are called *pirouettes* if performed from a single push-off and *Fouettés* (female variation) or *à la Seconde* turns (male variation) if turned

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consecutively with a short heel-down propulsion phase after each revolution. In the latter consecutive rotations, each revolution ends with the opening of the gesture leg to the front and a short heel-down phase. Laws (1986a) describes this openness to the front as relevant for both aesthetics and balance control, while the latter proposition has yet to be empirically examined. While two or three revolution *pirouettes* are quite standard, highly skilled ballet dancers can perform up to eleven *pirouettes* from a single push-off. Traditionally, dancers perform 32 *Fouettés / à la Seconde* turns in the codas of classical ballets. This is demonstrated, for example, by the ballet dancer performing the Black Swan in the ballet Swan Lake. These consecutive turns are deemed successful the more consistent the repeated revolutions are. Specifically, when the dancer completes each revolution within the expected rhythm in a relatively stable position in space. When having a closer look at such performance, particularly in multiple rotations, ballet dancers adopt a typical gaze behaviour called spotting. Dancers fixate a target in front of them and keep their gaze fixed on that target while their torso continues to rotate. When this fixation can no longer be sustained, they whip the head around to overtake the torso and swiftly catch the front again.

The task of turning on one leg consecutively offers a big challenge to our motor control system. Shiriaev, Freidovich, and Manchester (2008) state that stabilising periodic movements such as in *pirouettes* is much more difficult than stabilising an equilibrium point such as during static balancing poses. These authors showed that programming a robot to perform *pirouettes* is mathematically highly involved. It can thus be assumed that our motor control system is challenged to its maximum when it comes to turn full-body rotations multiple times.

Therefore, such incredible feats pose the question: How do ballet dancers successfully perform the highly complex task of turning consecutively around their longitudinal axis without losing balance? Only a few studies thus far have examined *Fouetté* turns (Imura, Iino, & Kojima, 2008, 2010; Laws, 1979); specifically, focusing on how dancers produce momentum in each revolution to continue turning with constant angular speed. Over the last decades, the *pirouette*, however, has been investigated quite extensively from a biomechanical perspective (e.g., Laws, 1979; Laws & Fulkerson, 1992; Lin, Chen, Su, Wu, & Lin, 2014; Lott & Laws, 2012; Zaferiou, Flashner, Wilcox, & McNitt-Gray, 2017; Zaferiou, Wilcox, & McNitt-Gray, 2016b). It has been shown that dancers use individual strategies when generating rotational impulse during the push-off phase of a *pirouette* (Zaferiou, Wilcox, & McNitt-Gray, 2016a). Similarly, dancers use individual coordination strategies in the supporting leg of *pirouettes* to sustain performance (Lott & Xu, 2020). From all joint motions measured in the study by Lott and Xu (2020), the ankle joint has the largest deviations, which shows the importance of ankle joint motion during the turning phase of the pirouette. Specifically, during rotation, the dancer must sustain balance by maintaining the centre of mass (COM) over the base of support (BOS; i.e., the supporting foot). Since the dancer is not a rigid body, minimal adjustments are necessary during rotation to achieve a high number of revolutions (Lott & Laws, 2012). Movement in the BOS and thus the ankle joint indicates that the dancer is making such adjustments to maintain alignment of the BOS under the COM (Lott & Xu, 2020). A recent publication by Lott (2019) identified movement of the BOS as the main mechanism for maintaining balance in high numbers of *pirouettes*. In this study, movement of the BOS (quantified as the supporting foot path length) was the only significant predictor of performance when compared with five other measures for balance. Greater path lengths per revolution were associated with the completion of a higher number of revolutions. In interpreting these findings, Lott (2019) suggests that there could be an optimal amount of BOS movement. While such movement is necessary from a biomechanical perspective, the author recognizes that it is idealized for the dancer turns on the spot from an aesthetical perspective. Therefore, optimising the movement in the supporting leg seems to be a critical strategy for maintaining balance in rotation. It has to be noted, however, that in *pirouettes*, dancers execute a single push-off and therefore, the BOS area doesn't change. This contrasts with *Fouettés/à la Seconde* turns, whereby the heel is lowered after each revolution for torque generation. This means that the BOS area of the standing foot increases in this active propulsion phase, which can help to reorient the centre of mass over the base of support. For turning multiple rotations of *pirouettes*, this is not possible.

When it comes to the role of spotting in rotation, research is limited. One study has investigated the effect of different spotting heights on force production during push-off of a *pirouette* (Cicchella & Caminiti, 2016). The authors found that a lower spotting height prompted longer time to peak force at push-off compared to performance with spotting heights at eye-level or slightly higher. Thus, it seems that the position of a visual reference influences the push-off phase in *pirouettes*. However, no analysis of performance during the turning phase with different spotting heights was conducted in this study. Another recent study showed that learning *pirouettes* with a spotting instruction (as compared to no such instruction) negatively affected the balance in *pirouettes* of novice dancers (Klostermann, Schärli, Kunz, Weber, & Hossner, 2020). The reason for this finding might be an inefficient spotting coordination in novices, which seems to hinder performance. Consequently, it may be assumed that the spotting coordination of highly skilled dancers has been expertly refined to rather support performance. The characteristics of such efficient spotting in dance have yet to be empirically described. Taken together, this limited research suggests that the effectiveness of spotting to enhance performance may be dependent on a visual reference and that spotting requires an effective use of head stabilization during rotation.

These two aspects – a visual reference for improved sensory feedback and head stabilization for balance control – have been discussed extensively in postural control research. In balance tasks without rotations, it is widely accepted that maintaining gaze on a visual reference in space improves balance (e.g., Strupp et al., 2003). Concerning head stabilization, it has been shown that a head-in-space stability strategy is superior to a head-on-trunk stabilization in a variety of postural control task, such as standing quietly and balancing on a beam or a slackline (Assaiante & Amblard, 1995; Pozzo, Levik, & Berthoz, 1995; Schärli, van de Langenberg, Murer, & Müller, 2013). These more fundamental findings support the notion that spotting towards a visual reference with effective head stabilization in space might indeed be crucial for successful dance rotations as well. Still, the exact characteristics of an optimal spotting technique and the implications of spotting in rotation have yet to be empirically defined.

Haber and Schärli (2021) conducted a Delphi Method survey to gather impressions of spotting from experts in the field. Professional ballet dancers, ballet teachers, and dance scientists participated in a three-round survey to narrow down relevant topics and evaluate consensus on the critical characteristics and uses of spotting. Besides the widely accepted reasons of spotting for balance control and dizziness reduction, the experts indicated that dancers spot to improve orientation and rhythm when turning. Notably, these latter two reasons for spotting have yet to be examined empirically. Moreover, experts indicated that spotting mainly becomes relevant in multiple rotations, calling for the investigation of spotting in high revolution contexts. As for the characteristics of successful spotting, head isolation and gaze specificity were identified as critical features. However, it should be noted that there was low consensus in ranking the relative importance of the suggested characteristics and uses of spotting; highlighting the importance of further studies to identify the most important aspects of the spotting technique in ballet dancers.

Based on the above theoretical considerations and the results of the study by Haber and Schärli (2021), the present study aims to investigate the influence of a visual reference on the performance of multiple rotations by highly skilled ballet dancers. Specifically, performance will be assessed by: 1) balance control, measured with BOS movement (Lott, 2019), 2) spotting duration, and 3) head isolation as a measure for head coordination, and 4) orientation of the body to the front. Moreover, as experts in the study of Haber and Schärli (2021) indicated that spotting is relevant in multiple rotations, we will use the consecutive turns of *Fouettés* and *à la Seconde* turns as a context to assess the influence of a visual reference on turning performance over time; that is, in the maintenance of performance over each consecutive revolution.

We hypothesise that 1) balance control improves with the presence of a visual reference point, as it does in balancing tasks without rotations (e.g., Strupp et al., 2003). In terms of spotting coordination, it is predicted that both 2) spotting duration and 3) head isolation increase with the presence of a visual reference. As has been shown in other non-rotating balancing tasks, a visual anchor point improved head stability in space (e.g., Pozzo, Berthoz, & Lefort, 1989). Therefore, we expect that an improved head stability in space can be translated to an improved spotting coordination in rotational movements (i.e., longer spotting duration and larger head isolation). Finally, as it has been shown that visual anchors help orientation when navigating thorough space (e.g., Hollands, Patla, & Vickers, 2002), we hypothesise that 4) a visual reference will improve orientation in consecutive rotations.

2. Methods

2.1. Participants

Sixteen dancers were recruited for the study. A call for elite dancers was circulated in a professional ballet company, a pre-professional ballet school, and within the freelance dance community (i.e., dancers working short term contracts between various companies) in Switzerland. It was indicated that dancers should self-identify as skilled turners and be able to consistently perform *Fouetté* and *à la Seconde* turns. Ultimately, four participants (three freelance dancers and one pre-professional student) were excluded from the study as they were not able to complete all turns as required in the protocol below. The twelve remaining dancers (8 male- and 4 female-identified) had a mean age of 26.8 ± 5.0 years and a mean of 15.5 ± 6.5 years of formal ballet training. All participants provided written informed consent prior to the start of the study and received monetary compensation for their time. The protocol was approved by the ethics committee of the local Faculty of Human Sciences and was carried out in accordance with the 1964 Declaration of Helsinki.

2.2. Data collection

The experiment was conducted in individual sessions in the Institute's sensory-motor laboratory, equipped with a 10-camera VICON T20 system (Vicon Motion Systems Limited, Oxford, UK) and covered in dance floor. Upon arriving to the laboratory, the dancers were given 30 min to perform a semi-standardized warm up; including jogging around the laboratory, joint mobilizations, and a self-led ballet barre. Next, relevant anthropometric measures were taken for the VICON full body Plug-in Gait model (i.e., height, mass, leg length, knee width, ankle width, shoulder offset, elbow width, and hand thickness). Following this, participants were equipped with retro-reflective markers (according to the Plug-in Gait model; (Davis, Õunpuu, Tyburski, & Gage, 1991)) and EOG electrodes (Ambu A/S, Ballerup, Denmark). One electrode was attached at the side of each eye, and the ground electrode was placed behind the right ear. The electrodes were connected to a small receiver box (Nexus-4, Mind Media, Herten, The Netherlands; weight: 140 g), which was secured tightly on the participants' back with a strap around the waist. In this way, the EOG signal could be recorded wirelessly. To ensure free head movement, the cables of the EOG electrodes to the receiver box had some slack and were fixed on the head with a head band. The EOG data was not considered in the present analysis.

Participants were then given five minutes to become comfortable moving with the equipment and practice a few *Fouetté* or *à la Seconde* turns. During this time, participants identified a preferred music tempo (i.e., either 126 bpm or 150 bpm; from two different parts of Don Quixote's coda piece). Traditionally, *Fouettés* are performed slightly slower than *à la Seconde* turns. However, tempo can vary further based on the choreography or style of ballet. Therefore, a choice of tempi was provided to the dancers. All dancers performing *Fouettés* chose to turn at the slower tempo, except one who chose the fast tempo. Similarly, all dancers performing *à la Seconde* turns chose to turn at the fast tempo, except one who chose the slow tempo. Prior to data collection, both static and dynamic calibrations were performed to optimize the full body model identification. For the static calibration, participants stood still for three seconds with their arms out to the side (i.e., T-position). For the dynamic calibration, participants went through a sequence of joint mobilizations, individually moving each limb and the head in all planes of motions. Then two familiarization trials were performed to introduce participants to the experimental procedure.

The experimental procedure for each trial proceeded as follows. Participants began standing at the back of the laboratory where the EOG receiver could be plugged into the VICON receiver via a cable. The recording was started with the systems connected to ensure synchronization of recordings. A researcher then unplugged the cable so the dancer could move freely and take their position on a mark in the centre of the space. The dancer assumed the T-position (as in the static calibration). After three seconds, a verbal cue was given to the dancer to prepare, at which point the dancer stood in fifth position (i.e., ballet-specific preparatory position with both legs externally rotated and one foot in front of the other). When the music started, the dancers performed the respective rotations. After finishing their rotations, dancers were asked to stand in fifth position once again for 30 s. The dancers then returned to the initial position at the back of the laboratory where the EOG receiver could be plugged in once again, so the 3D-motion and EOG recordings could be stopped while the systems were connected. Between test trials, participants were given a break of at least two minutes.

In terms of the specific rotations performed, a simpler double *pirouette* was completed in the familiarization trials so that participants could focus on practicing the rest of the experimental procedure. For the test trials, dancers performed a total of 14 continuous rotations. Due to the nature of the ballet dance technique, the nine male-identified dancers performed 12 *à la Seconde* turns followed by a double pirouette. The four female-identified dancers performed a double pirouette directly into 12 *Fouetté* turns. The placement of the double pirouette at the beginning and the end of the turns, respectively, is standard in ballet technique. All dancers turned to their preferred sides: Ten dancers turned to the right and two dancers to the left side.

The test trials were performed in two experimental conditions: (1) with a visual reference (i.e., Condition Dot; CD) and (2) without a visual reference (i.e., Condition Wall; CW). In CD, a GoPro camera (GoPro, Inc., San Mateo, CA, USA, dimensions: 4x6cm) was mounted at the dancer's eye height on the front white wall, which was 2.5 m from the dancer's starting position (see Fig. 1). In CW, the front white wall was left completely empty, and the GoPro was attached to office furniture in the back of the room (for CW). Thus, in CD the GoPro camera could be used as a visual reference – as a black "dot" on the wall – whereas no reference was provided in CW. Crucially, the participants were told that the GoPro camera was used for additional recording of the movements from different angles. It was not mentioned that it could or should be used for spotting.

As previous research (Solomon, Vijay, Jenkins, & Jewell, 2006) has found effects in head movements when turning towards a remembered visual cue (i.e., occluding a prior visual cue), we were cognizant of the potential influence of beginning the experiment with a salient visual reference. This issue precisely arose in feedback from prior participants piloting the experiment. Therefore, we wanted to make sure that all participant started without any visual reference to avoid such priming that may overemphasize the focus on spotting from the start. Therefore, the experiment was conducted in two identical blocks. The dancers started each block with 2 x CW followed by 2 x CD, with (at least) 2 min breaks between test trials as mentioned. After the first block, the dancers had an extended break of (at least) 4 min wherein they were asked to leave the lab and remain in the waiting room. The dancer then returned to the lab for the second block, starting again with CW, without the immediate effects of removing a visual cue. Accordingly, the order of trials was integrated as a factor in the analysis. Since ballet training and performance are marked by high repetitions of standardized exercises or set chorography (Allen, Nevill, Brooks, Koutedakis, & Wyon, 2012), we hypothesized that there would not be an effect for order in our elite sample, who is accustomed to performing consistent repetitions of technical movements.

At the end of the experiment participants were debriefed and thanked for their participation.

2.3. Measures

The performance of the *Fouetté* and *à la Seconde* turns was assessed with kinematic analyses. To this end, all trials were first reconstructed as three-dimensional recordings by the VICON Nexus software (v1.16) and marker labelling was then manually verified. Subsequently, all trials were exported as c3d-files and read into a self-written MATLAB script (MATLAB 2017b, MathWorks, Nattick, MA, USA). Gaps in the raw data were filled with spline interpolation. The data was then filtered with a third-order lowpass Butterworth

Fig. 1. Experimental setup.
Dancer turning in the laboratory in Condition Dot (CD). The visual reference (a mounted GoPro camera) was removed during Condition Wall (CW).

Filter, wherein the optimal cut-off frequency (8 Hz) was determined by residual analysis (Winter, 2009).

Critical events were algorithmically identified. Of the 14 revolutions completed in each test trial, eleven revolutions were examined in the analysis. Individual revolutions were identified from the moment when the dancer placed the supporting heel down in order to push off for the following revolution. The first eleven full *Fouettés* or *à la Seconde* turns were identified, excluding the preparatory double pirouette and final *Fouetté* into landing and similarly, excluding the first preparatory *à la Seconde* and the double pirouette to landing. The following dependent variables – described in detail below – were then calculated to assess: (1) Balance control, (2) spotting duration, (3) head isolation, and (4) orientation.

2.3.1. Balance control

While challenging to reduce the performance of such complex movements to one variable, performance of continuous revolutions may be best quantified by a measure of balance. During rotation, the dancer must sustain balance by maintaining the centre of mass (COM) over the BOS (i.e., the supporting foot). As mentioned in the Introduction and shown by Lott and Laws (2012), minimal postural adjustments are necessary during rotation to achieve a high number of revolutions. Movement in the BOS indicates that the dancer is making such adjustments to maintain alignment of the BOS under the COM (Lott & Xu, 2020). A recent publication by Lott (2019) showed that movement of the BOS– quantified as the normalized path length of the supporting foot – predicted turning performance of high revolution turns best. Therefore, we assessed balance control by the normalized path length of the supporting foot. For each revolution, the absolute path length of the marker at the base of the second metatarsal was divided by the height of the dancer.

2.3.2. Spotting duration

One parameter to assess the spotting coordination was the relative spotting duration. The relative spotting duration represents the proportion of the turn when the head is stable to the front (Fig. 2). The head stabilization phase (i.e., the spot) in each turn was identified from the maximum angular deceleration of the head towards the front to the maximum angular acceleration of the head away from the front. The relative spot duration was then calculated by dividing the duration of head stabilization (Fig. 2, bold black line) by the duration of the full head revolution, which includes the head stabilization plus the following head turn (Fig. 2, bold black line plus following bold grey line). Therefore, relative spotting duration is presented as a percentage of each revolution. In this way, the varied tempos of *Fouettés* and *à la Seconde* turns could be accounted for. Higher values indicate that dancers spent a longer portion of

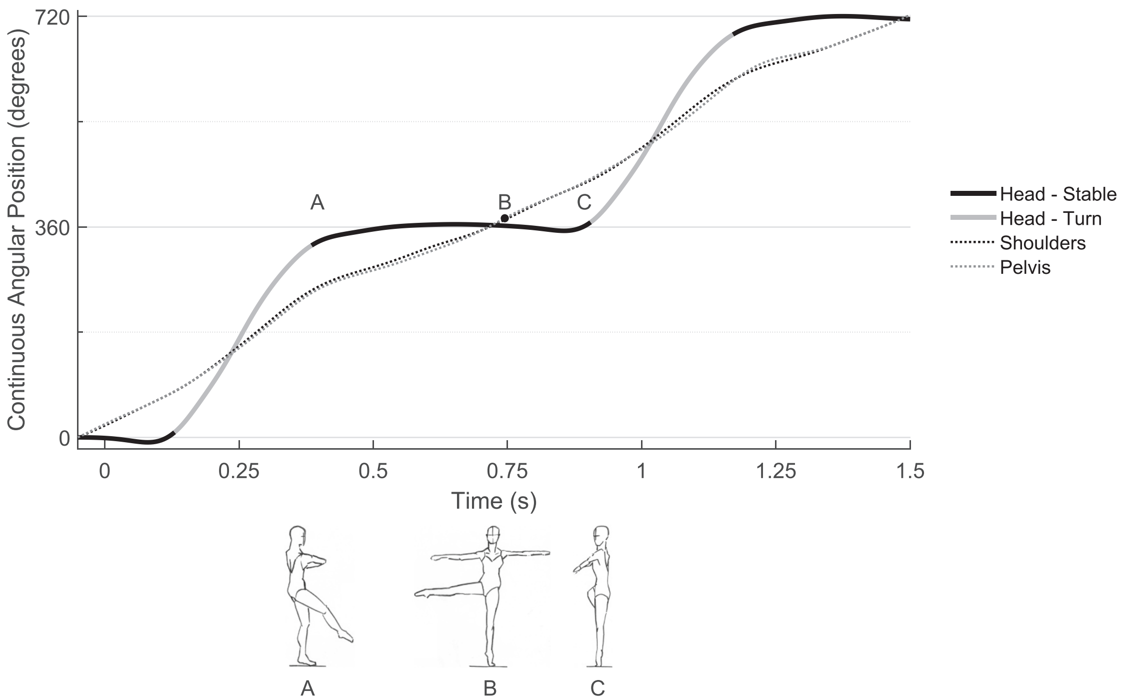

Fig. 2. Coordination of Continuous Revolutions.
Exemplary spotting coordination of one dancer during two full-body revolutions. The major gridlines indicate a full 360° revolution, starting with the dancer facing the front at 0°. The angular position of the normal vector from the head, shoulders, and pelvis are illustrated by the bold line, the black dotted line, and the grey dotted line, respectively. While the shoulders and pelvis turn very closely together, the head overtakes and lags behind the rest of the torso in a typical spotting coordination. The head stabilizes to spot the front at 360° (bold black line) and then quickly turns to overtake the torso once again (bold grey line). The black dot (B) indicates the dancer's pelvis orientation when the gesture leg is fully extended *à la Seconde*. The sketches below the figure illustrate (A) the start of spotting, (B) the *à la Seconde* position, and (C) the end of spotting, which repeat themselves in every continuous revolution.

the turn with the head stabilized towards the front.

2.3.3. Head isolation

The second parameter to assess the spotting coordination was head isolation (i.e., head-shoulder angle). Greater isolation of the head from the torso has been identified as a key characteristic of spotting (Haber & Schärli, 2021) and has been observed in expert dancers (Lin et al., 2014). In fundamental postural control research, head-in-space coordination has also proven advantageous compared to head-on-trunk coordination (Assaiante & Amblard, 1995). Head isolation was calculated as the absolute angular difference between the normal vectors of the head and the shoulders at the start of spotting. In Fig. 2, this can be understood as the difference between the head curve (bold line) and the shoulder curve (black dotted line) at the start of spotting (i.e., when the bold line changes from grey to black). A value of zero would indicate that the normal vectors of the head and the shoulders point in the same direction, which is also known as an 'en bloc' or head-on-trunk coordination. A larger angle indicates greater separation between the head and torso, or a more head-in-space coordination.

2.3.4. Orientation

Finally, in each revolution, we examined the dancer's orientation at the moment when they reach the *à la Seconde* position to the front (see Fig. 2, B). It is an aesthetical requirement of the turn for dancers to achieve this position towards the audience (Laws, 1986b). Moreover, spotting has been proposed to play a key role in orienting the dancer in space (Haber & Schärli, 2021). The *à la Seconde* position was identified as the moment when the gesture leg is furthest to the side. Then, the body orientation was calculated as the deviation of the normal vector of the pelvis from the expected orientation towards the front. A value of 0° indicates that the dancer is perfectly facing the front. A positive value indicates the dancers over-rotated the body, performing more than one full revolution; while a negative value indicates the dancer under-rotated, performing less than one revolution.

2.4. Statistical analysis

To recall, dancers performed eight experimental trials in a Wall-Dot-Wall-Dot order with a total of four experimental trials per condition. Within each trial, dancers performed multiple continuous revolutions, which were counted as turn numbers one to eleven leading up to the landing. Therefore, to address the hierarchical nature of the observations, the data was analysed using a linear ixed model (Gelman, Hill, & Vehtar, 2021).

The model was built as follows. The repeated measures were first accounted for by adding Participant as a random effect. Since the conditions were presented in a fixed CW-CD-CW-CD order, we controlled for potential ordering effects by adding Trial Order as a fixed effect. Next, to address the main research question regarding (1) the influence of a visual reference on performance, we included Condition as a fixed effect in the model. To this end, the true effect of Conditions could be better predicted with any potential order effect accounted for. Given the hypothesized dependence of spotting over continued performance (Haber & Schärli, 2021), the Turn Number was added as an additional fixed effect for CD and CW to address (2) whether dancers sustain performance differently as the Turn Number increases in each visual condition. The final predictive equation can be seen below:

$$y_{ij} = b_{0j} + b_1 Trial\ Order_{ij} + b_2\ Condition_{ij} + b_3 Turn\ Number_{Dot\,ij} + b_4 Turn\ Number_{Wall\,ij} + \varepsilon_{ij}$$
$$b_{0j} = b_0 + \mu_{0i}$$

where y represents the dependent variable for every participant, j, in each revolution, i.

The same model was run over the four dependent variables: balance control, spotting duration, head isolation, and orientation. The values for each of the eleven turns in the eight trials performed by twelve participants produced a total of 1056 observations. These values were exported from Matlab and input into the model in R (rStudio v 1.4.1717, PBC, Boston, MA). Standardized parameters were obtained by fitting the model on a z-transformed version of the dataset. A marginal ANOVA was then run over the standardized model to extract the effects for each predictor and to calculate the interaction effect of Turn Number x Condition, based on the split main effect of Turn Number. 95% Confidence Intervals (CIs) and p-values were computed using the Wald approximation. The significance level for all analysis was set at $\alpha = 0.05$.

3. Results

The results of the linear mixed model were first assessed in terms of the overall explanatory power (R^2). Notably, the consideration of standardized β-coefficients – which reflect the b_0, b_1, b_2, b_3 variables in the equation above – allow for the comparison of the relative contributions of each predictor in the model. For each unit change in a predictor (e.g., b_2: CD to CW), the β-coefficient reflects the respective change in the dependent variable. As in such regression-based analysis, larger absolute values indicate stronger contributions, and the sign represents the direction of difference. Moreover, the unstandardized predictors are also reported (B) to facilitate the interpretation of the regression. The unstandardized predictors can be directly interpreted in world units (e.g., the unstandardized coefficient for Turn $\text{Number}_{\text{Dot}}$ indicates how many degrees the body orientation changes when the dancer performs one additional turn in CD).

Table 1
Results of the linear mixed model for all outcome measures. Statistically significant values are marked in bold.

	Path length			Spot Duration			Spot Isolation			Orientation		
Predictors	*β*	*95% CI$_β$*	*B*	*β*	*95% CI $_β$*	*B*	*β*	*95% CI $_β$*	*B*	*β*	*95% CI $_β$*	*B*
Fixed Effects												
Intercept	0.09	−0.33, 0.51	18.98	−0.19	−0.61, 0.23	72.78	−0.20	−0.69, 0.29	55.80	0.19	−0.28, 0.65	6.67
Trial Order	**−0.03***	−0.05, −0.01	**−0.23***	0.02	0.00, 0.04	0.12	0.00	−0.01, 0.02	0.02	0.01	−0.01, 0.03	0.11
Condition [Wall]	**−0.22***	−0.42, −0.03	**−1.65***	−0.13	−0.33, 0.07	−0.77	0.06	−0.09, 0.20	0.65	**−0.17***	−0.34, −0.01	**−2.80***
Turn Number$_{Dot}$	0.02	0.00, 0.04	0.12	0.02	0, 0.04	0.10	**0.03****	0.02, 0.05	**0.39****	**−0.04****	−0.06, −0.02	**−0.62****
Turn Number$_{Wall}$	**0.04***	0.02, 0.06	**0.27***	**0.04***	0.02, 0.06	**0.21***	**0.02***	0.01, 0.04	**0.25***	−0.01	−0.02, 0.01	−0.10
Random Effects												
$σ^2$	0.54			0.54			0.29			0.39		

Note: $N = 1056$ for $n = 12$ participants. $β$ = Standardized Coefficients. CI$_β$ = Confidence Interval for Standardized coefficients. B = Unstandardized Coefficients. $σ^2$ = Residual Variance (Standardized)* $p < .05$ ** $p < .001$.

3.1. Balance control

The results of the linear mixed model for balance control – quantified as the supporting foot path length – can be seen in the first column of Table 1 and are illustrated in Fig. 3. The model's total explanatory power was substantial, conditional $R^2 = 0.46$. The results of the marginal ANOVA indicate that the effect of Trial Order was statistically significant, $F(1,1040) = 7.73$, $p = .006$, as dancers decreased the path length over the course of the experiment. Accounting for this ordering effect, Condition was also statistically significant, $F(1,1040) = 5.02$, $p = .025$; indicating that overall, dancers had smaller path lengths in CW. Additionally, the interaction effect of Turn Number x Condition was statistically significant, $F(2,1040) = 7.90$, $p < .001$. Referring to the split effects displayed in Table 1, we see that Turn Number is significant in CW, though not in CD. The effect in CW was statistically significant and positive indicating that dancers increased the path length of the supporting foot with continuous performance. However, with a visual reference in CD, dancers were able to sustain consistently efficient movements in the supporting foot, maintaining performance with no significant changes over time.

Against our initial hypothesis, Trial Order was found to be a significant predictor of performance. However, accounting for the observed Trial Order effect, we see that the effect of the Condition is still predominant in the model when comparing the β-coefficients ($|\beta_{Condition}| = 0.22 > |\beta_{Trial\ Order}| = 0.03$,).

3.2. Spotting duration

The results of the linear mixed model for spotting duration can be seen in the second column of Table 1 and are illustrated in Fig. 4. The model's total explanatory power was substantial, conditional $R^2 = 0.46$. The effect of Trial Order in the marginal ANOVA was not significant, $F(1,1040) = 3.60$, $p = .580$. The overall effect of the Condition was also statistically non-significant, $F(1,1040) = 1.70$, $p = .192$. While there was no general difference in the spotting duration in the two visual conditions, the visual conditions appeared to influence spotting duration during continuous performance. The interaction effect of Turn Number × Condition was statistically significant, $F(2,1040) = 7.88$, $p < .001$. Referring to the Turn Number effects in Table 1 and Fig. 4, we see that this interaction effect is driven by changes in spotting duration in CW. Dancers appear to spot longer towards the end of the turns when there is no visual reference.

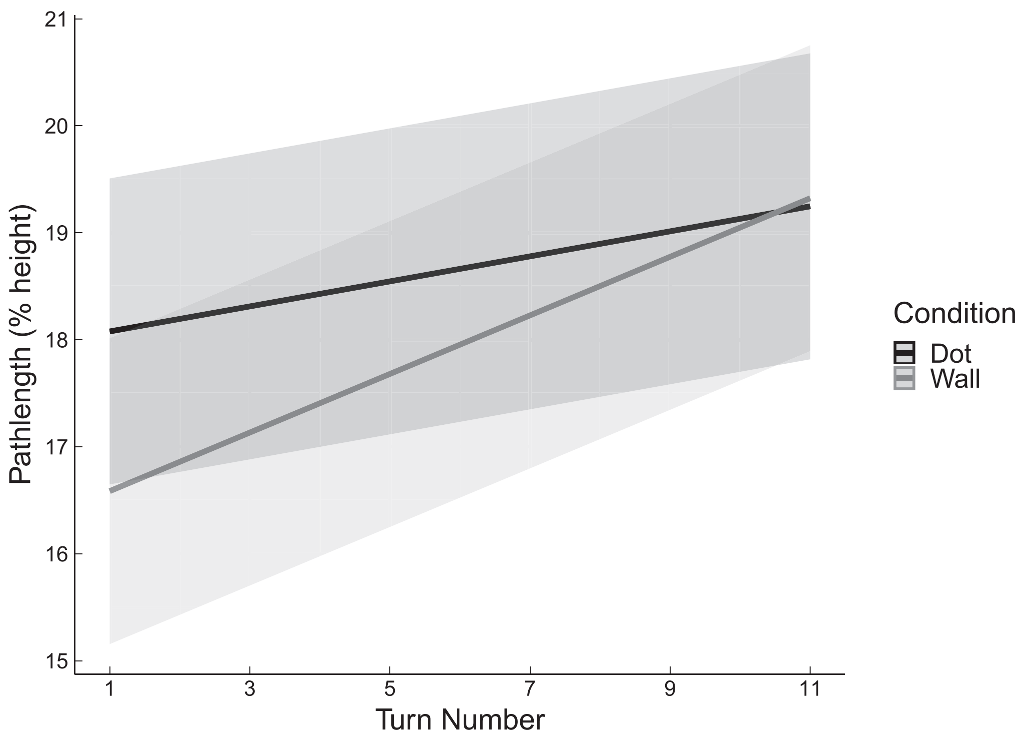

Fig. 3. Balance Control: Path length of the Supporting Foot.
Predicted values from the model of supporting foot path length over eleven consecutive revolutions of *Fouetté* and *à la Seconde* turns, with a visual reference (black line, CD) and without a visual reference (grey line, CW), given the average Trial Order Shaded regions represent ±1 standard deviation. The path length the supporting foot travelled in each revolution was normalized as a percentage of each dancer's height.

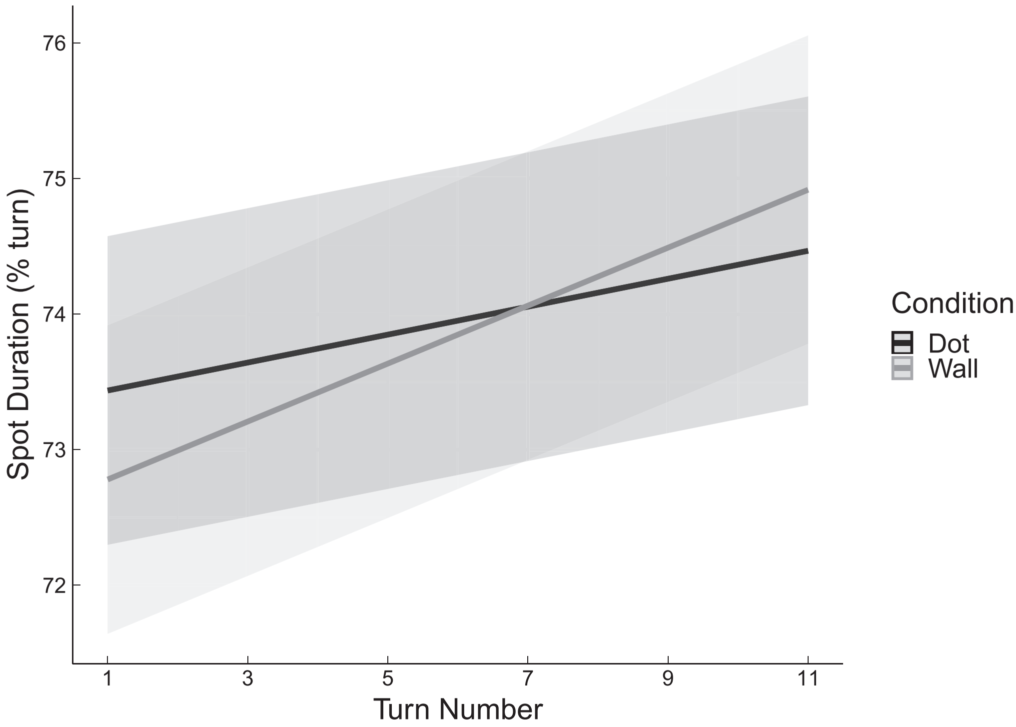

Fig. 4. Spotting Duration.
Predicted values from the model of spotting duration over eleven consecutive revolutions of *Fouetté* and *à la Seconde* turns, with a visual reference (black line, CD) and without a visual reference (grey line, CW), given the average Trial Order Shaded regions represent ±1 standard deviation. Considering the time for each full head revolution (i.e. Head Stable + Head Turn), the spotting duration is presented here as a the percentage of the full revolution in which the head is stable ([Head Stable / (Head Stable + Head Turns)]*100).

3.3. Head isolation

The results of the linear mixed model for head isolation are displayed in the third column of Table 1 and illustrated in Fig. 5. The model's total explanatory power was substantial, conditional $R^2 = 0.71$. In regards to the marginal ANOVA for spot isolation, there appeared to be no order effect over the experiment, with Trial Order statistically non-significant, $F(1.1040) = 0.04$, $p = .843$. There was similarly a statistically non-significant effect of Condition, $F(1,1040) = 0.57$, $p = .451$. Meanwhile, the interaction effect of Turn Number x Condition was statistically significant, $F(2,1040) = 14.09$, $p < .0001$; indicating that dancers increased the isolation of the head from the torso over continuous performance in both conditions.

3.4. Orientation

The results of the linear mixed model for Orientation are displayed in the fourth column of Table 1 and illustrated in Fig. 6. The model's total explanatory power was substantial, conditional $R^2 = 0.61$. The marginal ANOVA indicated that Trial Order did not influence orientation, $F(1,1040) = 0.58$, $p = .447$. However, there was a significant difference between the Conditions, $F(1,1040) = 4.22$, $p = .040$. Overall, dancers better oriented themselves to the front with a visual reference. The interaction effect of Condition x Turn Number was also significant, $F(2,1040) = 102.8$, $p < .001$. As the continuous revolutions progressed, dancers were able to orient themselves even better in CD.

4. Discussion

Our study is the first to investigate the influence of a visual reference on the performance of the consecutive *Fouetté / à la Seconde* turns in professional ballet dancers. Turning performance was assessed in terms of balance control, spotting duration, head isolation, and orientation. Overall, with a visual reference, dancers had larger path lengths in the supporting foot and better orientation towards the front. Yet, the visual conditions did not appear to influence spotting duration nor head isolation overall. Rather, across all dependent measures, the visual condition seemed to influence performance over time. Without a visual reference, dancer increased the foot path length and the spotting duration over consecutive turns to reach a suitable strategy for control. While with a visual reference, dancers were able to better orient themselves in each subsequent revolution with consistently efficient movements in the supporting leg. In both conditions, dancers utilized greater head isolation over time.

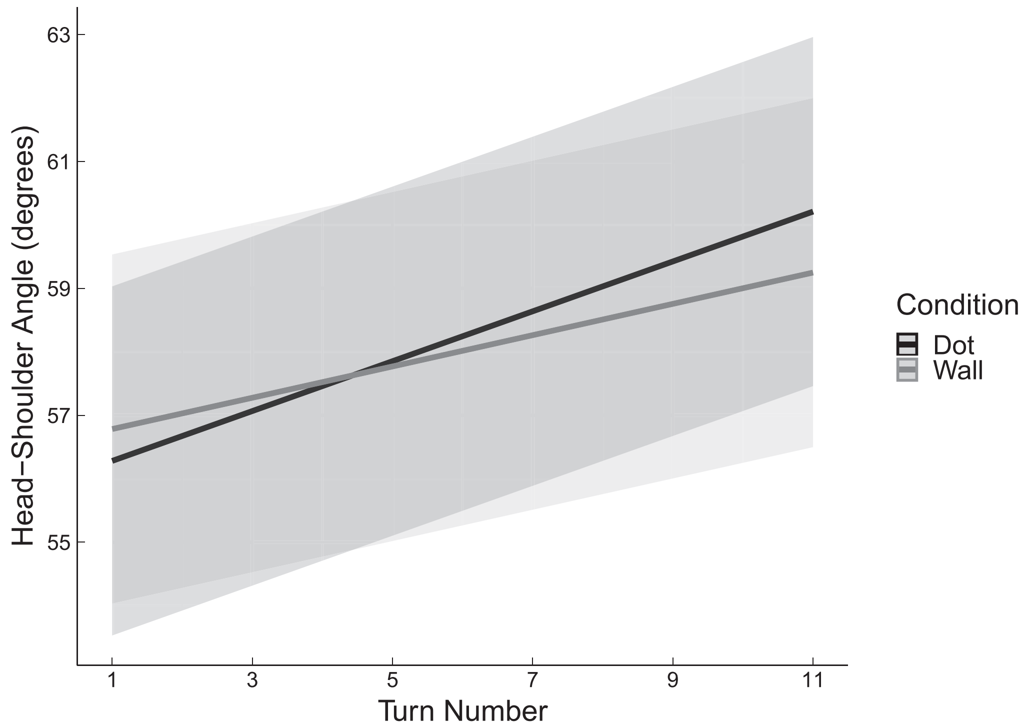

Fig. 5. Head Isolation.
Predicted values from the model of head isolation over eleven consecutive revolutions of *Fouetté* and *à la Seconde* turns, with a visual reference (black line, CD) and without a visual reference (grey line, CW), given the average Trial Order. Shaded regions represent ±1 standard deviation. Head isolation is quantified as the degree of separation between the head direction and the torso direction as the start of spotting.

With regard to balance control, overall, the dancers showed larger supporting foot path lengths in the condition with a visual reference. In the study by Lott (2019) greater path lengths per revolution were associated with the completion of a higher number of revolutions. Thus, an optimal strategy would be moving the BOS adequately to consistently meet the biomechanical demands of stability, while optimising the efficiency of such movements to meet the aesthetic demands of ballet. In the present findings, the larger path lengths observed in the condition with a visual reference could be marked as the necessary postural adjustments for optimal balance control in consecutive rotations. The dancers in the study of Lott (2019) showed normalized path lengths of 14% per revolution for five *pirouettes*. This is comparable to the consistent 18% per revolution found in our study in the condition with a reference point. Since dancers must negotiate a push-off phase during each revolution in *Fouetté* and *à la Seconde* turns – rather than a single push-off before five *pirouettes* (Lott, 2019) – a larger BOS movement is to be expected.

Moreover, it can be hypothesized that successful and efficient adjustments in the supporting foot would be repeated to sustain performance. However, if an initial adjustment is not sufficient, the following adjustment must be greater. It seems that a visual reference helped the dancers to keep the path length, and thus their balance control, constant over consecutive rotations, as supported by the non-significant interaction between Condition [Dot] x Turn Number. Alternately, balance control was less consistent over time in the condition without a visual reference. In CW, dancers started with smaller path lengths and significantly increased their adjustments over the course of the turns to reach similar path lengths as in CD. Thus, our data suggest that a visual reference supports optimal postural adjustments from the start of consecutive turns; whereas without a visual reference the dancer seems to find an optimal strategy for balance control after several revolutions only. We can thus accept our first hypothesis that a visual reference helps balance control in consecutive turns in highly skilled ballet dancers.

In relation to head isolation, several studies have shown that stabilising the head in space improves balance control (e.g., Assaiante & Amblard, 1993) and is a sign of expertise (Lin et al., 2014; Schärli, Keller, Lorenzetti, Murer, & van de Langenberg, 2013). Thus, we can assume that a larger head-shoulder angle (i.e., head isolation) might be a more superior coordination pattern than an 'en bloc' or head-on-torso coordination in multiple rotations. We hypothesized that a visual reference facilitates such a head stabilization-in-space. However, we did not find a difference in head isolation between conditions. This finding is in contrast to that of Solomon et al. (2006) who found greater head-trunk separation in walking turns when participants turn towards a reference point. Nonetheless, we observed an increased head isolation over the course of turning in both conditions. Independent of the presence of a visual reference, dancers seem to increase their head isolation and thus head-in-space stabilization over time. Thus, it can be assumed that an increased head isolation is a crucial factor for the successful continuation of turning performance. The head might be an important reference frame for the dancers to keep up with the rhythm of the music, especially when fatigue of leg muscles and dizziness kicks in.

Contrary to our expectations, we did not find an increase in spotting duration during consecutive turns with a visual reference as

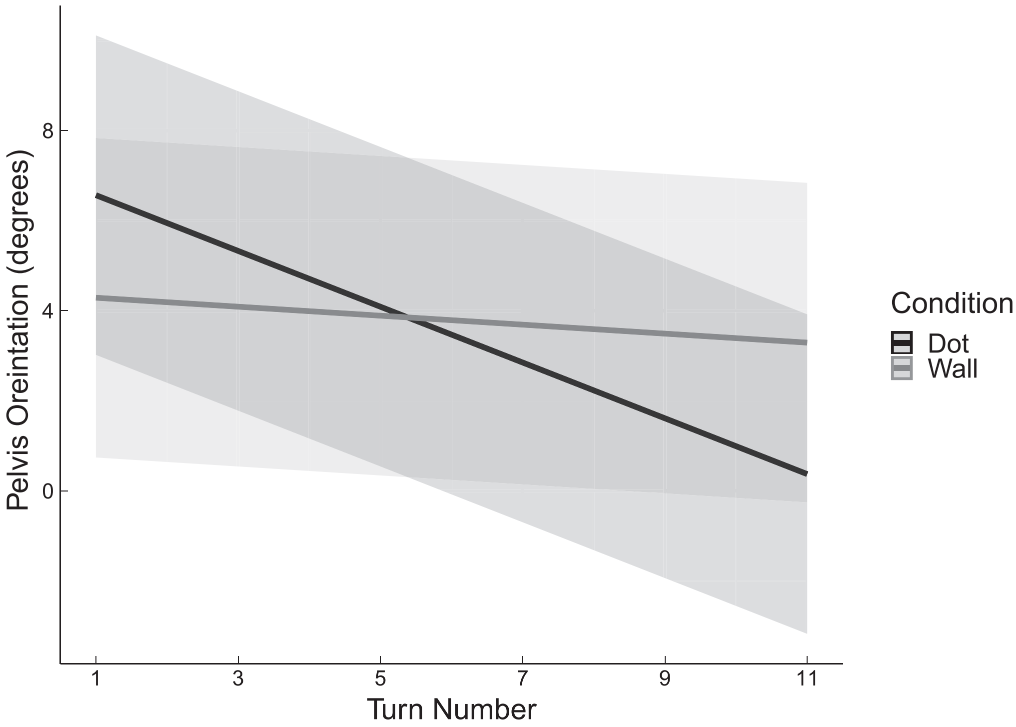

Fig. 6. Orientation.
Predicted values from the model of orientation over eleven consecutive revolutions of *Fouetté* and *à la Seconde* turns, with a visual reference (black line, CD) and without a visual reference (grey line, CW), given the average Trial Order. Shaded regions represent ±1 standard deviation. Orientation is measured as the normal vector from the pelvis when the dancer is in the *à la Seconde* position. Perfect orientation to the front is at 0°, while positive values indicate the dancer over-rotated to complete more than 1 revolution.

compared to no reference. It could be that when a visual reference is available, feedback about one's own position in space is taken in more quickly than when this is not the case. This is supported by our result that dancers spotted longer in CW as the turns progressed. Without a clear visual reference, dancers might have tried to increase the time to gather visual feedback about their position in space by spotting to the front longer. Natrup et al. (2020) investigated the gaze behaviour of gymnasts who performed somersaults on a trampoline. As in the rotations of our dancers, who aimed to reach the same orientation to the front after each rotation, the gymnasts had to orient themselves in space to safely land on the trampoline bed after their rotations in the air. Interestingly, these authors found that the more skilled gymnasts were fixating their gaze on the trampoline bed later and thus shorter than the less skilled ones. This finding supports the notion that a longer fixation period is not necessarily functional for such highly complex movement tasks. Therefore, a prolongation of the spotting duration is not necessary if a clearly contrasted visual reference is available. The timing of the fixation might be more relevant. Also, while head stabilization has proven valuable in stationary balancing task (e.g., Schärli, Keller, et al., 2013), an increased spotting duration during whole-body revolutions can be disruptive to the turn dynamics (Haber & Schärli, 2021; Laws, 1979). Thus, it can be concluded that the prolonged spotting duration towards the end of multiple rotations in the condition without a visual reference may not be functional for turning success.

Finally, we investigated whether a visual reference influences orientation of the dancers during multiple rotations. In ballet, precise body orientation in space is key not only to meet choreographic and aesthetic demands, but also to ensure smooth partnering interactions. The aim of *Fouettés / à la Seconde* turns is to always end one revolution with the body facing the front. It has been shown that visual anchors help when navigating through space by supporting a head-centred reference frame, which helps full-body coordination in such direction changing movements (Hollands et al., 2002). Thus, a visual reference might improve body orientation during multiple ballet rotations as well. Indeed, we observed that dancers had an improved orientation to the front with a visual reference – both overall and over the course of turning – when compared to performance with no such reference. The dancers generally over-rotated their bodies at the start of the revolutions. However, only in the condition with a visual reference did dancers more precisely align themselves to the front the longer they turned. Thus, as hypothesized, we can state that a visual reference improves the orientation of the dancers in space during continuous turning performance.

In conclusion, our findings underline the importance of a visual reference for performance of multiple rotations around the longitudinal axis, such as *Fouettés* and *à la Seconde* turns in the ballet technique. A visual reference seems to be relevant mainly for balance control and orientation. Additionally, it appears that a visual reference becomes increasingly relevant over the course of multiple rotations. For dance practice, this means that the availability of a spotting light in theatres – a central light placed at the back of the theatre or a spotting object in the dance studio, which dancers can fixate – seems to be a good idea for supporting dancers' performance of multiple rotations on stage and in the learning environment.

In the following, we emphasise some of the limitations of our study. First, despite our efforts to remove all additional visual references in CW, the laboratory space did have some other potential reference objects. The motion capture cameras at corners of the ceiling and the workstation at the back may have come into view, which might have diminished the influence of the visual reference object in the front on the turning performance. Second, we did not counter-balance the conditions, which might have influenced the outcome. This decision was determined based on previous literature and feedback from piloting. Additionally, as we had high-level ballet dancers, we did not expect an ordering effect during the experiment. Therefore, we accounted for a potential order effect in our analysis. Third, we investigated *Fouettés / à la Seconde* turns, which can be seen as a particular style of rotation. Thus, our findings cannot be generalized to other dance turns directly and need to be interpreted cautiously. In specific, in the *Fouettés / à la Seconde* turns the heel of the supporting leg is lowered after each revolution, which for example is not the cause in *pirouettes*.

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CRediT authorship contribution statement

Andrea Schärli: Conceptualization, Methodology, Investigation, Formal analysis, Data curation, Writing – original draft, Writing – review & editing. **Catherine Haber:** Conceptualization, Methodology, Software, Investigation, Formal analysis, Data curation, Visualization, Writing – review & editing. **André Klostermann:** Conceptualization, Supervision, Writing – review & editing.

Declaration of Competing Interest

None.

Data availability

Data will be made available on request.

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