# The spatiotemporal control of expert tennis players when returning first serves: a perception-action perspective

José A. Navia

[a]Facultad de Ciencias de la Actividad Física y del Deporte (INEF), Universidad Politécnica de Madrid, Madrid. ORCID: 0000-0003-1218-5033

Twitter: @naviagallego

Carlos Avilés

[b]Facultad de Educación, Universidad Complutense de Madrid, Madrid. ORCID: 0000-0001-9540-1808

Twitter: @caavilesv

Matt Dicks

[c]School of Sport, Health and Exercise Science, University of Portsmouth, United Kingdom. ORCID: 0000-0001-6584-2733

Twitter: @MattDicks7

Luis M. Ruiz

[a]Facultad de Ciencias de la Actividad Física y del Deporte (INEF), Universidad Politécnica de Madrid, Madrid. ORCID: 0000-0002-9678-5986

Twitter: @lmruizperez

Corresponding author: Carlos Avilés.

Rector Royo Villanova, 1, Ciudad Universitaria, 28040 Madrid or caviles@pdi.ucm.es

As accepted for publication in **Journal of Sports Sciences**, 1st September 2021.

## Abstract

The aim of the current experiment was to examine the spatiotemporal control of expert tennis players while executing first service returns within a representative experimental setting. We recruited and tested twelve male expert tennis players in hard courts. A comprehensive analysis of the timing (eleven temporal variables analyzed at 300 Hz) and performance success of the return actions were carried out, while simultaneously considering task constraints such as the accuracy and the speed of the serves. Temporal organization of return actions were scaled relative to the server's racket-ball contact (5 ms), an adaptation of fly-time of the split-step, which resulted in consistent landings (133 ms), and initiation of lateral movements towards the ball –with no response errors– after the server's stroke (around 177 ms). Poorer returns occurred when responding to accurate serves accompanied by late trunk movements towards the ball. Returners scaled the timing of the response to the unfolding action of the serve in order to support both spatial and temporal accuracy. These novel findings highlight the significance of the study of fast-ball sports in representative settings and offer further detail on the spatiotemporal control of skilful perception-action.

**Keywords**: Ecological psychology; expertise; sport performance; tennis returns

## 1. Introduction

Elite sports are replete with situations where athletes execute highly-skilled movements against competing opponents. The aim of many scientists has been to reveal the possible attributes that underpin such sporting excellence (Williams & Jackson, 2019). In particular, researchers have aimed to measure the underlying mechanisms of expertise in fast-ball sports where athletes are faced with situations that offer minimal time for perception-action. As such, examples of commonly studied fast-ball sports include batting in cricket (Mann et al., 2010), baseball (Gray, 2002) and the penalty kick in football (Dicks, Button, et al., 2010b; Navia et al., 2017). One example of a fast-ball situation that has received a large amount of research interest is the return of serve in tennis (Avilés et al., 2019). The specific temporal demands for the player returning 'flat' fast serves leaves approximately 700 ms from the point of server racket-ball contact until the ball reaches the other side of the court (Vaverka et al., 2003), yet expert tennis players are still able to return the ball accurately to a remarkably high degree (Triolet et al., 2013). A question of interest for researchers has been to identify whether skilled players are capable of using advance information from an opponent's movements (e.g., Farrow & Abernerthy, 2003), and the game context (Farrow & Reid, 2012) in order to accurately predict ball-flight spatial trajectory prior to its onset. A prominent consideration has been whether such early predictions underpin elite performance by providing players with more time to coordinate action (Müller & Abernethy, 2012; Vernon et al., 2018). Indeed, this primary research question has motivated some seminal works in racket sports, which have shown that experts are able to better predict event outcomes more accurately than less-skilled performers (Abernethy et al., 2001).

Recent findings have led some researchers to question the assumption that elite athletes do predict spatial ball-flight trajectories well in advance of their onset. For example, through the observational coding of professional tennis matches, Triolet and colleagues (2013) revealed that the frequency of lateral motion of the player's body or racket before the opponent's stroke (see also Mecheri et al., 2019) –even when returning second serves– was marginal. This important observation was further emphasised in a recent systematic review of anticipation of tennis serves (Avilés et al., 2019). These authors reported that studies of expert tennis players consistently demonstrated that lateral movement towards the (expected trajectory of the) ball prior to racket-ball contact rarely occurs under representative conditions when responding to first serves. Hence, the returners' actions towards the ball seem to occur between 160 - 170 ms after the server's stroke (Mecheri et al., 2019; Triolet et al, 2013). Importantly, the results from Triolet and colleagues (2013) and other studies (Mecheri et al., 2019; Shim et al., 2005) have also revealed infrequent response errors (i.e., movement to the wrong spatial location) when elite players initiate their responses after racket-ball contact of the serve. Analysis of the kinematic actions of tennis serves have suggested that specifying information concerning ball trajectory unfolds close to the point of racket-ball contact (Huys et al., 2008). Hence, starting the lateral movement of the returning action before server's ball-racket impact increases the likelihood of a decrease in spatial accuracy.

Such findings have helped to inform the contemporary proposal that skilled performers use kinematic information not only to spatially adapt their movements to the trajectory of the ball but also to adjust the timing of the return action (Dicks et al., 2019; van der Kamp et al., 2018). Thus, it is proposed that expertise may not manifest itself as early predictive judgements that offer a maximum time period to execute an action, but in contrast, skill can be conceptualised as the accurate calibration of actions that are scaled to the spatiotemporal demands of the task (Fajen, 2005). Hence, the accurate scaling of one’s own action capabilities (e.g., agility) to the spatiotemporal demands (e.g., time available) provides a maximum time period before initiating the response in order to use more reliable information. By way of example, Mecheri and colleagues (2019) reported that tennis players who were more powerful – and therefore could cover an equivalent distance in a shorter time – waited later before initiating their actions and produced more consistent returns of serve (see also Dicks, Davids et al., 2010). Such results add further empirical support to the suggestion that elite performance is not only predicated on spatial anticipatory behaviour (Avilés et al., 2019) but that experts prospectively control their actions, utilising unfolding information via affordance based control (Fajen, 2005). However, despite the efforts made by researchers to investigate the spatiotemporal control of actions during serve returns (Avilés et al., 2014; Mecheri et al., 2019), the extent to which highly-skilled performance can be explained by the accurate coupling of return actions that are timed relative to service actions is still limited, as the spatiotemporal constraints of the tasks have not been simultaneously considered. To this end, research suggests that return performance is influenced by both the speed and the accuracy of serves (Haake et al., 2000; O’Donoghue & Ballantyne, 2004). Faster serves reduce the time to contact and serves in the corner of the service court increase the distance to reach the ball, so both shape the time available to complete the return action (Navia et al., 2017).

The purpose of this study was to build on existing literature (e.g., Mecheri et al., 2019) and further current understanding of the spatiotemporal control of expert tennis players in a competitive training situation, that simulated match-play conditions. We sought to do so whilst considering, for the first time in literature, the speed and accuracy of the serve as a covariate for timing and performance. In addition, in order to offer unique experimental rigour, the timing of actions was analysed with a detail of 300 Hz, which allowed us to accurately quantify the spatiotemporal control of actions. Thus, the current study addressed the recommendations provided in Avilés et al (2019) recent systematic review of anticipation in tennis. In line with previous findings (Mecheri et al., 2019; Shim et al., 2005; Triolet et al., 2013), players were expected to initiate the split-step and lateral displacement movements after the racket-ball contact as a result of scaling to the opponent's unfolding action (Navia et al., 2017). We also hypothesized a decrease in player performance when facing faster and more accurate serves (van der Kamp et al., 2018) given the increased spatiotemporal demand.

## 2. Method

### 2.1 Participants

Twelve right-handed male expert tennis players (age: 21.4 ± 5.5 years old) volunteered to participate in the study. Based on the International Tennis Federation (ITF), International Tennis Number (ITN) ranking criterion (ITF, 2004) all players were categorized at ITN 1 or 2, with extensive professional tournament experience (12.83 ± 6.3 years). Six of the participants were established Association of Tennis Professionals (ATP) players, with two ranked in the top ten for male singles in the season(s) preceding or following data collection. The remaining six players were highly ranked nationally within Spain. All participants were undertaking extensive regular training at the time of the experiment (21.7 ± 6 h/week). The participants acted as both servers and returners during the experiment. Before testing, all participants provided written consent and ethical approval was obtained from the local University's ethics committee.

## 2.2 Material

Personal racquets of participants and Dunlop Fort All Court tennis balls were used during testing. The timing of the serve and return actions were recorded at 300 Hz using a high-speed camera (Casio Exilim F1), located behind the receiver ~4.5 m from the baseline. Two 25Hz cameras (Cannon MV950 and JVC GY-301E) situated 5 and 4 m behind the baseline captured the serve and return locations, respectively. Speed of the serve was registered with a radar (Sports Radar SR3600), placed at a height of 2.9 m and 2.9 m behind the server, and connected to a laptop that displayed and recorded the velocity of the ball (Sports Radar Data Acquisition Software V.1.1. Technology). Tape was used to mark target areas for the serves and the different areas of the return (Hornery et al., 2007). Recordings from the cameras were analyzed using Kinovea V.0.8.7. and then coded into an excel sheet.

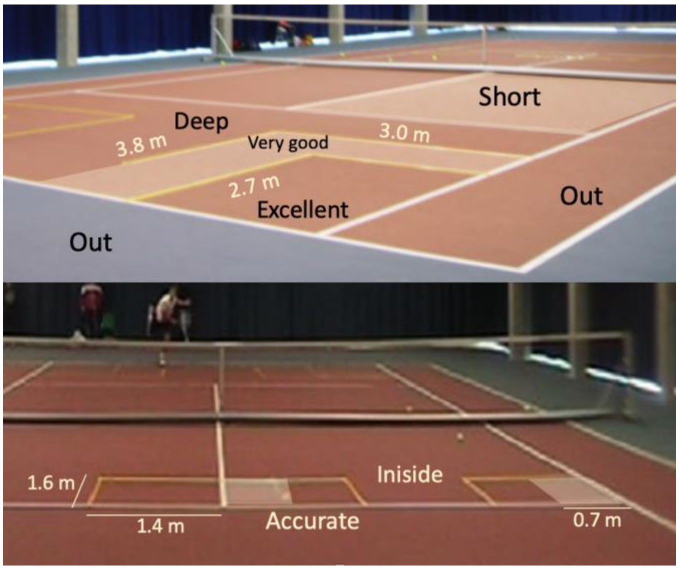

**Figure 1.** Areas of the return (top) and targets for the serve (bottom).

## 2.3 Procedure and design

All testing was carried out on a tennis hard-court. Prior to testing, all participants undertook a warm-up that consisted of 5 minutes of jogging and stretches, 10 minutes of tennis rallies, and 5 minutes of specific serve and return actions (i.e., familiarization). The experiment consisted of a period of simulated match-play, during which, each participant carried out 50 returns. After each set of 10 trials, players changed the side of the court (3 sets at deuce and 2 at advantage). Testing was organized in pairs of participants in such a way that one player started serving and another player returning. Roles were interchanged (server-returner) after the 3rd, 6th and 8th set of 10 trials until the completion of 100 trials (i.e., 50 returns for each participant). Players were told to follow their habitual routine and perform exactly as they would do during serves and returns. There was a mean period of 13 seconds between trials –a time which is within the stipulated time frame in tournaments–, meaning participants had regular periods of rest during testing. Moreover, participants had 2.5 minutes break between sets. In total, testing took between 45 and 60 min for a pair of players. Tennis players were encouraged to perform flat serves as fast as possible towards the targets placed in T and wide areas (Mecheri et al., 2019). The direction of serve was randomized and equally distributed (T and wide) and servers were provided with instruction of where to aim before each trial. Returners –who did not know the direction of the serves– were encouraged to return as best as possible.

## 2.4 Measures

A total sample of 600 trials were obtained across all participants. 249 of the serves (41.5%) were directed out of the service box and were therefore not used for analysis. In addition to the side of the court (deuce vs advantage) that the serve was hit, and serve placement (T or wide), the speed of the serve was also registered for each trial. Return performance and serve accuracy were assessed from the video recordings (Figure 1). Following prior research (Avilés et al., 2014; Hornery et al., 2007), a scale was applied to returns according to the landing location of the ball (Figure 1 top): 0 points for an ace, 1 for a short, 2 for a deep, 3 for a very good, and 4 for an excellent return. Using a software grid, accurate serves were registered when the ball bounced in the cornered half of the target (see Figure 1, bottom). Some behavioral measures of the returner were also coded: (i) whether or not a player moved before the server's racket-ball impact (i.e., directional split-step, see below); (ii) whether the player moved in the same direction as the serve (i.e., movement direction); and (iii) whether the player's foot landing after the split-step was congruent or incongruent with the ball direction (Avilés et al., 2014).

In order to add further detail to previous research (Avilés et al., 2002; Filipcic et al., 2017; Gillet et al., 2010), nine temporal events of the returning players were coded relative to the server's stroke. Negative values denoted events before server's racquet ball-contact and positive values were recorded for events after racquet-ball contact. As depicted in Figure 2, preparatory actions involved: (i) Heel take-off of the back leg; (ii) Impulse (when the lumbar area –representing the center of gravity– moved upwards); (iii) Heel take-off of the front leg; (iv) Split-step (front foot take-off); (v) First foot landing – toe contact – following the split-step; and (vi) Second foot landing – toe contact – following the split-step. (vii) Trunk onset was defined as the first observable movement of the trunk, arms or racquet, towards the actual ball trajectory. Finally, (viii) Return indicated the moment of the return stroke (or ball passing by the returner in the case of an ace). In some of the aces, the returner did not try to contact the ball after being aware that ball was far away from their range, so the return was not coded in such instances (*N* = 37). (ix) Directional split-step was also coded only in the instances (*N* = *36*) when the player initiated a lateral split-step –correct or not– with any part of the body towards either side of the court before the server's impact. Two additional spatiotemporal variables were computed: (x) Fly time –from the initiation of the split-step to the first foot landing; and (xi) Movement time –from Trunk onset to Return (Avilés et al., 2002; Avilés et al., 2014; Vaverka et al., 2003). A second researcher analyzed 13 variables from 20 randomly selected trials, obtaining a global Cronbach' alpha = 0.94.

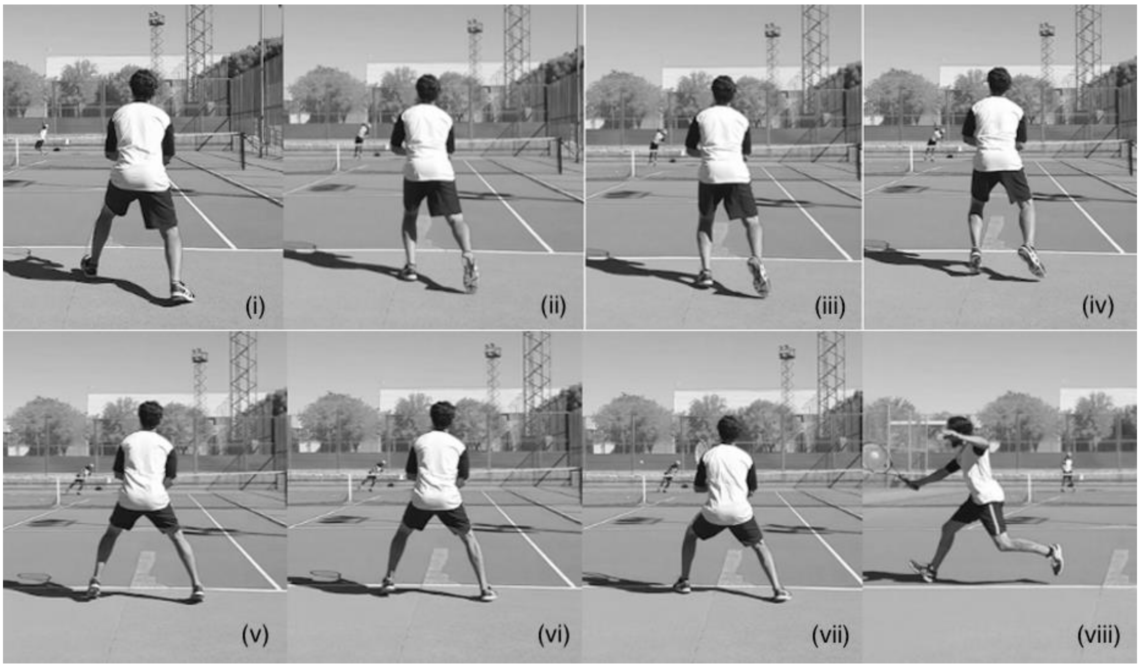

**Figure 2.** Events coded in during the sequence of the return: (i) back heel take off; (ii) impulse; (iii) front heel take-off; (iv) split-step; (v) first foot landing; (vi) second foot landing; (vii) trunk onset; and (viii) return stroke.

## 2.5 Statistics

Due to the hierarchical nature of collected data (i.e., residuals of observations are not independent), multilevel linear models were applied:  Level 1 trials, Level 2 participants. Initial exploratory analysis included normality tests (K-S, skewness and kurtosis) and visual inspection (histograms and Q-Q plots). After descriptive and correlational analysis, we first tested in mixed models random intercepts with fixed slopes, then random intercepts and slopes, and finally examined interactions between fixed factors whenever possible (Field, 2018). Row scores were used as predictors (without centering). After the models, Q-Q and scatterplots checked normality and homoscedasticity. Effect size for Bonferroni post-hoc were expressed in *d*, with values of 0.2, 0.5 and 0.8 for small, medium and large effect, respectively (Cohen, 1988). The level of significance for all analysis was set at $\alpha = 0.05$. Using a within factor repeated measures ANOVA test provided.

Using a within factor repeated measures ANOVA test provided by G*Power 3 (Faul et al., 2007) a post-hoc power of 0.83 (1-β) was computed considering a medium effect size ($\eta_p^2 = 0.06$), $\alpha = 0.05$, and 50 trials per 12 participants. IBM SPSS V.25 (Armonk, NY: IBM Corp., USA) and R-based software jamovi V.1.6.1 (www.jamovi.org) were employed for statistical analysis and figure production.

## 3. Results

The mean service speed was 176 km/h (*Mdn* = 176, *SD = 10*). The entire temporalization of the return (from back heel take-off to return stroke) took slightly less than a second (Figure 3). Return actions followed this temporal sequence: heel take-off of the back leg (*M* = -253 ms, *Mdn* = 250, *SD* =116), impulse (*M* = -228 ms, *Mdn* = -233, *SD* = 83), heel take-off of the front leg (*M* = -117 ms, *Mdn* = -117, *SD* = 56) and split-step (*M* = 5 ms, *Mdn* = 0, *SD* = 53). The average fly-time was 126 ms (*Mdn* = 123, *SD* = 50) before landing, first contacting with one foot (first foot landing, *M* = 131 ms, *Mdn* = 133, *SD* = 27) and then with the second foot (*M* = 156 ms, *Mdn* = 150, *SD* = 33). On average, tennis players moved towards the ball 177 ms after the server's stroke (i.e., trunk onset: *Mdn* = 176, *SD* = 42). The mean time of the return strokes was 692 ms (*Mdn* = 678, *SD* = 67), which represented an average movement time of 519 ms (*Mdn* = 509, *SD* = 77).

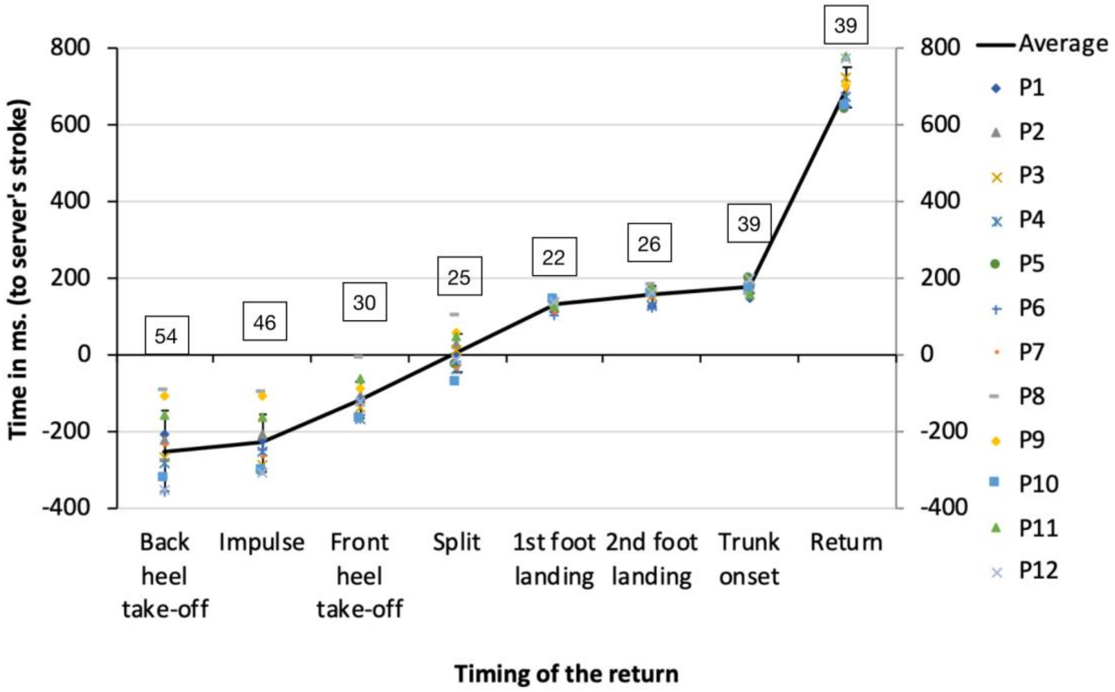

**Figure 3**. Individual profiles of participants' temporalization of returns. Mean intra-participant variability (ms) is displayed in squares as the average of individual SD's.

In most of the trials (89.8%), players performed a neutral split-step (a forward movement), followed by a trunk movement towards the ball. In 10.2% of the trials players initiated a directional split-step (lateral movement towards either side) before the completion of the server's action (*M* = -122 ms, *Mdn* = -115, *SD* = 84 ms), followed by a trunk movement towards the actual direction of the ball. Mixed-model analysis (random intercept and fixed slope, *BIC* = 3614.07, *ICC* = 0.11) did not reveal any differences in Trunk onset (i.e., actual movement towards the ball) between trials preceded by directional split-step (estimated marginal mean of Trunk onset = 182 ms) and neutral split-step (estimated marginal mean of Trunk onset = 176 ms), *estimate* =

5.47, $F(1,350.79) = 0.57$, $p = 0.452$. However, returners moved towards the wrong direction significantly more often when they carried out a directional split-step (12 out of 36 cases) than when a neutral split-step was performed (2 out of 313); as confirmed by mixed-model analysis (random intercept and fixed slope, $BIC = 87.64$) $estimate = -4.36$, z = -5.5, $\chi^2(1) = 30.26$, $p < 0.001$.

From the 351 trials, 207 (59%) were performed from the deuce side of the court and 144 (41%) were performed from the advantage side. Considering the direction of serves, 179 (51%) were directed towards the T (central) and 172 (49%) were directed wide (Supplemental 1). Performance of the returns were similar for both sides of the court and serve directions, as all $p$'s > 0.05 in main effects and interactions. Return success was primarily influenced by the accuracy of the serve (145 trials landed in the ‘accurate’ area and a further 206 landed in the ‘inside’ area, see Figure 1 bottom). Unlike serve speed, the model significantly improved when the time of trunk onset was added (Figure 4a), indicating that an earlier trunk onset facilitated better responses. Hence, the best final model (random intercepts, fixed slopes, $BIC = 1199.89$, $ICC = 0.02$) that explained the results included serve accuracy, $F(1, 351) = 45.89$, $estimate = -0.95$, $p < 0.001$ and trunk onset, $F(1, 309) = 14.07$, $estimate = -0.006$, $p < 0.001$.

Preparatory actions and the initiation of the return action were not temporally constrained by the speed of the serve, as no main effects for speed were found on impulse, split, fly-time, foot landings or trunk onset (all $p$'s > 0.05). Rather, results revealed that players regulated their split-step relative to information from the server’s impact of the ball, as indicated by the results of three variables. First, the split-step (i.e., last foot tip take-off) was tightly coupled with racquet ball-contact ($M = 5$ ms, $Mdn = 0$, $SD = 53$). Second, as Figure 4b depicts, players adjusted their fly time, so that later splits were followed by earlier first foot landings, mixed-model (random slopes and intercept, *BIC* = 3138.15, *ICC* = 0.65), *F*(1,11.2) = 74.81, *estimate for intercept*= 122.25, *estimate for split* = -0.55, *p* < 0.001. Third, first foot landing occurred significantly more often with the opposite foot (60%) compared to the same foot (40%) as the direction of the ball, (random intercept, *BIC* = 480.29), *z* = 2.55, *estimate* = 0.41, *p* = 0.011. Actually, mixed model (random slopes and intercept, BIC = 3588.41, ICC = 0.13) revealed an earlier trunk onset when landing with the opposite foot first (estimated marginal mean of Trunk onset = 170 ms) than when landing with the same foot first (estimated marginal mean of Trunk onset = 190 ms), *estimate* = -19.93, *F*(1,10.52) = 7.23, *p* = 0.022.

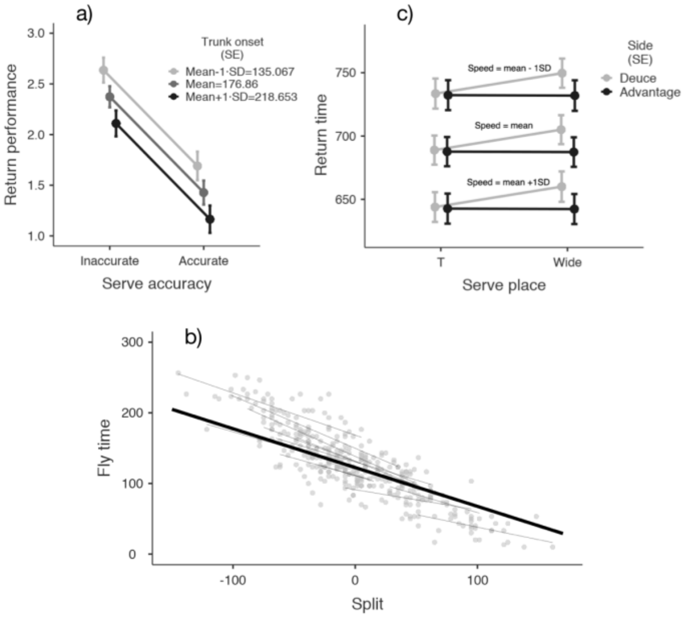

**Figure 4.** Performance of tennis players. a) Return performance as a function of accuracy of the serve and lateral trunk and/or racquet lateral initiation times; b) Relationship between split moment and fly time during the split-step. Solid line and fine lines represent regression model and individual random effects, respectively; c) Times of the return stroke by side, place and speed of the serve.

While speed had no effect on return performance, impulse, split, fly-time, foot landings or trunk onset, it was observed that later return strokes occurred when responding to slower serves, and also when returning wide serves that were executed from the deuce side of the court (Figure 4c). Mixed-model (fixed slopes and random intercepts, *BIC* = 3044.41, *ICC* = 0.68) revealed a main effect for speed, *F*(1,314) = 261.31, *estimate* = -4.44, *p* < 0.001, for side, *F*(1,299,02) = 7.40, *estimate* = 17.69, *p* = 0.007, serve place, *F*(1,298.53) = 5.40, *estimate* = 0.33, *p* = 0.021, and an interaction between speed and serve direction, *F*(1, 299.64) = 5.30, *estimate* = -16.45, *p* = 0.022. Post-hoc tests with Bonferroni correction revealed that return time of Deuce-Wide serves significantly differed from Deuce-T, *t*(308)= -3.44, *d* = 0.39, *p* = 0.003, and from both Advantage T and Wide, *t*(307)= -3.73, *d* = 0.42, *p* < 0.001 and *t*(308) = 3.47, *d* = 0.39 *p* < 0.001, respectively. No further pairwise comparisons were significant.

## 4. Discussion

The aim of the current study was to examine the spatiotemporal control of expert tennis players when facing first serves (Avilés et al., 2019). In line with recent studies (Mecheri et al., 2019; Triolet et al., 2013) players were found to accurately calibrate their split-step and lateral displacement movements to the opponent's unfolding actions. Preparatory movements (i.e., heel take-off of the back leg, impulse and heel take-off of the front leg) occurred well before serve release –from -253 ms onwards– whilst, measures revealed a relatively high variation between and within participants. In contrast, during the time-course of the serving action, there was a notable coupling between the split-step and the server's stroke, as players consistently performed the split-step at the time of racquet-ball contact (around 5 ms). As previously reported (Mecheri et al., 2019), the timing of the landing action was very consistent. During the split-step, a systematic regulation of the fly time length was observed as players landed at approximately the same time just after ball release (131 and 156 ms for first and second foot landing, respectively). Furthermore, landings after the split-step, occurred slightly but significantly more frequently with the contralateral foot to the ball direction. This behaviour reflects a coordinative adaptation to support the following lateral displacement towards the ball (Avilés et al., 2014; Elliot et al., 2009), which occurred 177 ms after racquet-ball contact. A future research challenge is to examine the actual prevalence of contralateral foot landings –and subsequent behaviours– with respect to expertise and/or individual capabilities (e.g., agility) and in changing contexts (e.g., court type).

In comparison with extant literature (Shim et al., 2005; Triolet et al., 2013), one particular advance of the current research is the examination of service speed relative to the spatiotemporal control of serve returns. One might expect that the speed of the serve would not have an impact upon the timing of return actions before (heel take-offs, impulse) or around (split-step) the service racket-ball contact, as information pertaining to ball speed is not available –and predicting the speed of the serve based on server's preparatory actions seems unlikely given their similarity among trials. A question that remained unsolved was whether the speed of the serve somehow affected the timing of the return actions that take place after the serve. Results indicated that fly time, foot landings, and moving of trunk onset were not significantly influenced by the ball speed. This finding suggests that elite tennis players utilise information from the movement kinematics of the server, in order to regulate the temporal control of the return action (Mecheri et al., 2019). Speed of the serve only influenced the time of the return stroke, meaning that slower serves resulted in players taking more time to cover the court before completing the return action (i.e., the ball took longer to arrive at the racket). Contrary to suggestions in the literature (O'Donoghue & Ballantyne, 2004), speed of the serve in this experiment was not found to determine the returners' success. Serves in the current experiment were consistently executed at considerable speed (*M* = 176 km/h) given that participants were performing at an expert level and that all serves were executed as first serves. Subsequently, the key determinant for the return success appeared to be the accuracy of the serve, which could be due to the trajectory followed by accurate serves (directed to the corners of the service court). A later initiation of lateral action towards the ball (trunk onset) also resulted in poorer performance, as it reduced the temporal margin to perform the returning stroke (van der Kamp et al., 2018). This result suggests that returners might perform outside a safe spatiotemporal boundary (Fajen & Devaney, 2006). That is, when attempting to return serves hit to the corners of the service court, one might have expected that the tennis players would have moved earlier to enable adequate scaling of their response relative to their action capabilities (Dicks, Davids et al., 2010, Navia et al., 2017). However, such earlier scaling would have led to less accurate responses (Shim et al., 2005) as an increased number of movement corrections occur with an earlier directional split-step.

Collectively, these novel findings lend empirical support to the proposal that the temporal control (when to move) of real-time interceptive actions are regulated in tandem with the spatial control (where to move) of actions (Dicks et al., 2019). This interpretation is supported by the findings of Navia and colleagues (2017), who revealed that world-class futsal goalkeepers adopted a gaze pattern when saving penalty kicks that was commensurate with the pick-up of information for the temporal control of the saving action. Specifically, this study reported that information exploited prior to penalty taker foot-ball contact appeared to inform on the time to contact between the penalty taker and the ball, rather than spatial anticipation. Information that subsequently unfolded around and following contact (kicking action and ball flight) appeared to subsequently guide the spatial control of the interceptive action, a proposal which is supported by the results from the current study. Hence, tennis players calibrated the return in order to support the spatio-temporal control of movement rather than extending the temporal margin (which led to a reduced response accuracy). Thus, the temporal calibration findings of goalkeepers facing penalties in soccer (Dicks, Davids, et al., 2010) or futsal (Navia et al., 2017), and the apparent inaccuracy of scaling of actions might be actually indicative of an adaptive behaviour.

As considered, one concern among tennis researchers and professionals is the extent to which expert players anticipate the direction of the ball under representative conditions (Avilés et al., 2019; Triolet et al., 2013). Results indicated that in 90% of trials, players did not exhibit any lateral movement before the completion of the serve (i.e., neutral split-step towards the front). Importantly, the examination of actual lateral movement of the trunk and/or racquet towards the ball (i.e., trunk onset) revealed that players did not obtain any performance advantage when a lateral split-step was performed prior to the racket-ball contact in the service action. Conversely, when lateral movement initiation did occur prior to racket-ball contact, this led to an increase in the number of response corrections (Dicks, Button, et al., 2010a). The observation that moving too early led to an increase in the number of response corrections is not a trivial issue in tennis. There is growing evidence that has identified the importance of perception-action as a contributory factor toward reducing the risk of anterior cruciate ligament (ACL) injuries (Collins et al., 2016). To this end, the current results suggest that a facet of skill that may reduce ACL injury risk is an accurate scaling of actions relative to critical events in fast-ball sports. Thus, a requirement for future research is to better understand the role that perception-action can play in sport as a means of reducing injury risk. To this end, a particularly fruitful avenue may be to develop training interventions that focus on improving the timing and calibration of actions (Dicks et al., 2015).

## 5. Conclusions

The current experiment provides a detailed examination of the performance (service-return action, 11 variables analysed at 300 Hz., spatiotemporal constraints considered) of expert tennis players. In line with previous research (Mecheri et al., 2019), the results indicate that players regulate the timing of returns relative to the time course of the opposing serve action. Return success was determined by the trade-off between regulating actions to ensure response accuracy (spatial control), while optimizing the margin of time to act (temporal control) (Navia et al., 2018). Future research should explore the control of actions as a function of both individual action capabilities (Dicks, Davids, et al., 2010) and changing spatiotemporal demands of the task (e.g., court type, quality of server, etc.). A further step in the understanding of skilful performance should also involve the investigation of the interaction between different sources of information (e.g., preferences of the server) in the control of actions (Cañal-Bruland & Mann, 2015; Navia et al., 2013; Vernon et al., 2018). For instance, whether awareness of information pertaining to an opponent's serving pattern impacts upon the spatiotemporal control of the return.

## Acknowledgments and funding

This work was supported by the ITF Development Department under Grant ITF RG 2006/08 awarded to the last author. We thankfully acknowledge the support provided by the ITF, Spanish Tennis Federation (Coaching Area), Madrid Tennis Federation and Catalan Tennis Federation. In coordination among them, the federations facilitated the access to professional tennis players and provided the facilities to carry out the data collection.

## Disclosure statement

The authors report no conflict of interest.

## References

Abernethy, B., Gill, D., Parks, S., & Packer, S. (2001). Expertise and the perception of kinematic and situational probability information. *Perception & Psychophysics, 30*, 233-252.

Avilés, C., Benguigui, N., Beaudoin, E., & Godard, F. (2002). Developing early perception and getting ready for action on the return of serve. *ITF Coaching & Sport Science Review, 28*, 6-8.

Avilés, C., Navia, J. A., Ruiz, L. M., & Martínez de Quel, Ó. (2019). Do expert tennis players actually demonstrate anticipatory behavior when returning a first serve under representative conditions? A systematic review including quality assessment and methodological recommendations. *Psychology of Sport and Exercise, 43*, 16-26. https://doi.org/10.1016/j.psychsport.2018.12.015

Avilés, C., Ruiz, L. M., Sanz, D., & Navia, J. A. (2014). Adaptive and reactive skills involved in the return of serve in tennis. *ITF Coaching & Sport Science Review, 22*(64), 6-8.

Cañal-Bruland, R., & Mann, D. L. (2015). Time to broaden the scope of research on anticipatory behavior: a case for the role of probabilistic information. *Frontiers in Psychology, 6*, 1518. https://doi.org/10.3389/fpsyg.2015.01518

Cohen, J. (1988). *Statistical power analysis for the behavioural science* (2nd ed.). Academic Press.

Collins, J. D., Almonroeder, T. G., Ebersole, K. T., & O'Connor, K. M. (2016). The effects of fatigue and anticipation on the mechanics of the knee during cutting in female athletes. *Clinical Biomechanics, 35*, 62-67. https://doi.org/10.1016/j.clinbiomech.2016.04.004

Dicks, M., Araujo, D., & van der Kamp, J. (2019). Perception-action for the study of anticipation and decision making. In A. M. Williams & R. Jackson (Eds.), *Anticipation and decision making in sport* (pp. 181-199). Routledge. https://doi.org/10.4324/9781315146270-10

Dicks, M., Button, C., & Davids, K. (2010a). Availability of advance visual information constrains association-football goalkeeping performance during penalty kicks. *Perception, 39*(8), 1111-1124. https://doi.org/doi:10.1068/p6442

Dicks, M., Button, C., & Davids, K. (2010b). Examination of gaze behaviors under in situ and video simulation task constraints reveals differences in information pickup for perception and action. *Attention, Perception, & Psychophysics, 72*(3), 706-720. https://doi.org/doi:10.3758/APP.72.3.706

Dicks, M., Davids, K., & Button, C. (2009). Representative task designs for the study of perception and action in sport. *International Journal of Sport Psychology, 40*(4), 506-524.

Dicks, M., Davids, K., & Button, C. (2010). Individual differences in the visual control of intercepting a penalty kick in association football. *Human Movement Science, 29*(3), 401-411. https://doi.org/10.1016/j.humov.2010.02.008

Dicks, M., van der Kamp, J., Withagen, R., & Koedijker, J. (2015). Can we hasten expertise by video simulations?" Considerations from an ecological psychology perspective. *International Journal of Sport Psychology, 46*, 587-607.

Elliot, B., Reid, M., & Crespo, M. (2009). *Technique Development in Tennis Stroke Production*. ITF

Faul, F., Erdfelder, E., Lang, A.-G., & Buchner, A. (2007). G*Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior Research Methods, 39*, 175-191. https://doi.org/10.3758/bf03193146

Fajen, B. (2005). Perceiving possibilities for action: On the necessity of calibration and perceptual learning for the visual guidance of action. *Perception, 34*(6), 717-740. https://doi.org/10.1068/p5405

Fajen, B., & Devaney, M. (2006). Learning to Control Collisions: The Role of Perceptual Attunement and Action Boundaries. *Journal of Experimental Psychology: Human Perception and Performance, 32*(2), 300-313. https://doi.org/10.1037/0096-1523.32.2.300

Farrow, D., & Abernethy, B. (2003). Do Expertise and the degree of perception-action coupling affect natural anticipatory performance? *Perception, 32*, 1127-1139. https://doi.org/10.1068/p3323

Farrow, D., & Reid, M. (2012). The contribution of situational probability information to anticipatory skill. *Journal of Science and Medicine in Sport, 15*(4), 368-373. https://doi.org/10.1016/j.jsams.2011.12.007

Field, A. (2018). *Discovering statistics using SPSS* (5th ed.). Sage.

Filipcic, A., Leskosek, B., & Filipcic, T. (2017). Split-Step Timing of Professional and Junior Tennis Players. *Journal of human kinetics, 55*, 97-105. https://doi.org/10.1515/hukin-2017-0009

Gillet, E., Leroy, D., Thouvarecq, R., Mégrot, F., & Stein, J.-F. (2010). Movement-Production Strategy in Tennis: a Case Study. *The Journal of Strength & Conditioning Research, 24*(7), 1942-1947. https://doi.org/10.1519/JSC.0b013e3181dc4622

Gray, R. (2002). Behavior of college baseball players in a virtual batting task. *Journal of Experimental Psychology: Human Perception and Performance, 28*(5), 1131-1148. https://doi.org/10.1037//0096-1523.28.5.1131

Haake, S. J., Rose, P., & Kotze, J. (2000). Reaction time-testing and Grand Slam Tie-break data. In S.J.Haake & R.Coe (Eds.), *Tennis Science and Technology* (pp. 269-276). Blackwell Science.

Hornery, D. J., Farrow, D., Mujika, I., & Young, W. B. (2007). Caffeine, carbohydrate, and cooling use during prolonged simulated tennis. *International Journal of Sports Physiology and Performance, 2*(4), 423-438. https://doi.org/10.1123/ijspp.2.4.423

Huys, R., Smeeton, J., Hodges, N., Beek, P., & Williams, A. M. (2008). On the dynamic information underlying visual anticipation skill. *Perception & Psychophysics, 70*, 1217-1234. https://doi.org/doi: 10.3758/PP.70.7.1217

ITF. (2004). *International tennis number manual*. Tennis Development Department of the International Tennis Federation. Retrieved from: http://www.tennisplayandstay.com/media/131802/131802.pdf

Mann, D. L., Abernethy, B., & Farrow, D. (2010). Action specificity increases anticipatory performance and the expert advantage in natural interceptive tasks. *Acta Psychologica, 135*(1), 17-23. https://doi.org/10.1016/j.actpsy.2010.04.006

Mecheri, S., Laffaye, G., Triolet, C., Leroy, D., Dicks, M., Choukou, M. A., & Benguigui, N. (2019). Relationship between split-step timing and leg stiffness in world-class tennis players when returning fast serves. *Journal of Sports Sciences, 37*(17), 1962-1971. https://doi.org/10.1080/02640414.2019.1609392

Müller, S., & Abernethy, B. (2012). Expert anticipatory skill in striking sports: A review and a model. *Research Quarterly for Exercise and Sport, 83*(2), 175-187.

Navia, J. A., Avilés, C., López, S., & Ruiz, L. M. (2018). A current approach to anticipation in sport. *Estudios de Psicología, 39*, 1-19. https://doi.org/10.1080/02109395.2017.1412705

Navia, J. A., Dicks, M., van der Kamp, J., & Ruiz, L. M. (2017). Gaze Control During Interceptive Actions With Different Spatiotemporal Demands. *Journal of Experimental Psychology: Human Perception and Performance, 43*(4), 783-793. https://doi.org/10.1037/xhp0000347

Navia, J. A., van der Kamp, J., & Ruiz, L. M. (2013). On the Use of Situational and Body Information in Goalkeeper Actions during a Soccer Penalty Kick. *International Journal of Sport Psychology, 44*, 234-251. https://doi.org/10.7352/IJSP2013.43.000

O’Donoghue, P., & Ballantyne, A. (2004). The impact of speed of service in Grand Slam singles tennis. In A. Lees, J. F. Khan, & I. Maynard (Eds.), *Science and racket sports III* (pp. 179-184). Routledge.

Shim, J., Chow, J., Carlton, L., & Woen-Sik, C. (2005). The Use of Anticipatory Visual Cues by Highly Skilled Tennis Players. *Journal of Motor Behavior*, *37*(2), 164-175.

Triolet, C., Benguigui, N., Le Runigo, C., & Williams, A. M. (2013). Quantifying the nature of anticipation in professional tennis. *Journal of Sports Sciences, 31*(8), 820-830. https://doi.org/10.1080/02640414.2012.759658

van der Kamp, J., Dicks, M., Navia, J. A., & Noël, B. (2018). Goalkeeping in the soccer penalty kick. It is time we take affordance-based control seriously! *German Journal of Exercise and Sport Research, 48*(2), 169-175. https://doi.org/10.1007/s12662-018-0506-3

Vaverka, F., Stromsik, P., & Zhanel, J. (2003). Player preparation for service-return - A biomechanics viewpoint. In S. Miller (Ed.), *Proceedings of the 2nd ITF International Congress on Tennis Science & Technology* (pp. 193-198). International Tennis Federation Ltd.

Vernon, G., Farrow, D., & Reid, M. (2018). Returning Serve in Tennis: A Qualitative Examination of the Interaction of Anticipatory Information Sources Used by Professional Tennis Players. *Frontiers in Psychology, 9*(895). https://doi.org/10.3389/fpsyg.2018.00895

Williams, A. M., & Jackson, R. C. (2019). Anticipation in sport: Fifty years on, what have we learned and what research still needs to be undertaken? *Psychology of Sport and Exercise, 42*, 16-24. https://doi.org/https://doi.org/10.1016/j.psychsport.2018.11.014