SPATIAL SPEED-ACCURACY TRADE-OFF IN INTERNATIONAL BADMINTON PLAYERS PERFORMING THE FOREHAND SMASH

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Speed and accuracy of the badminton smash are critical components for successful performance. Fifty-two participants data were collected using a Vicon 3D Motion capture system (400 Hz) at the BWF Glasgow World Championships (2017). The purpose of this study was to identify and compare spatial speed-accuracy trade-off (SATO) relationships amongst international badminton players performing the forehand smash, under two conditions: maximal speed (MS) in the direction of a target; and maximal speed aiming to hit the centre of a target (TAR). Exploratory and confirmatory cluster analyses revealed three groupings: Fitts' inverse relationship (FIR), no relationship (NR) and alternate inverse relationship (AIR). Findings indicate that for international badminton players 80–99% of maximum speed is the threshold for achieving the highest levels of spatial accuracy.

KEYWORDS: cluster analysis, shuttlecock speed, racquet sports, spatio-temporal

INTRODUCTION: In ballistic, rapid aiming sports skills such as the badminton smash, the ability to maximise shuttlecock speed and attain a high level of spatial accuracy is crucial for successful performance (El-Gizawy et al., 2014; Kwan et al., 2011; Sakurai & Ohtsuki, 2000). Fitts' Law (1954) has acted as the basis for spatial speed-accuracy trade-off (SATO) analyses for over half a century, advocating an inverse relationship where rapid movements lead to less accurate spatial outcomes, and slower movements lead to more accurate spatial outcomes. Subsequent research has shown that elite handball players are able to throw close to maximum speed (75 - 85%) but still achieve greater spatial accuracy than novices (García et al., 2013). Cluster analysis has become a more prevalent method for facilitating mining of multi-dimensional data. A metric relatable to characteristics of the data can be used to statistically quantify similarity between objects during clustering (Rein et al., 2010). From this patterns or relationships in inter- and intra-individual performance can be identified (Ball and Best, 2007). Using both exploratory and confirmatory cluster analyses, the purpose of the study was to identify and compare any emergent SATO relationships utilised by international badminton players performing the forehand smash, under two spatio-temporal conditions.

METHODS: Fifty-two (males: 29; females: 23) elite international badminton players (23.9 ± 4.8 years; 1.77 ± 0.08 m; 70.8 ± 7.9 kg) from 26 nations in 4 continents competing at the BWF Glasgow world championships (2017), participated in the study (BWF world rankings: 23:849). All procedures were explained to the participants and informed consent was obtained following ethics committee guidelines. Data were recorded on practise courts at the BWF Glasgow World Championships (2017) using an 18 camera Vicon 3D motion capture system (400 Hz; OMG Plc, Oxford, UK). Seven pieces of retro-reflective tape (3M Scotchlite) were put on the racket face and shaft, one 14 mm retro-reflective marker was placed on the base of the racket handle and one piece of retro-reflective tape was attached around the cork of each shuttlecock. A Badenko shuttlecock feeder (BKL V1.0) was positioned on one side of the badminton court (distance to side tramline: 1.58 m; distance to rear tramline: 3.24 m) to feed the shuttlecocks towards the participant. An international badminton player qualitatively selected an appropriate frequency (0.25 Hz), trajectory (launcher tilted to maximum range) and power setting (10 watts) for match-representative lifts. A ⌀ 3m target (Podium 4 Sport) was placed flat on the centre line of the opposite side of the court (target centre distance to side tramline: 3.05 m; rear tramline: 2.13 m). Target location was qualitatively selected by an international badminton player as a likely smash winning shot landing location. A ratio scale with 4 concentric rings (r = 26.5 cm increment for each ring) and 1 concentric centre circle was used to score accuracy, assigning an integer for each zone, from zero (centre circle; most accurate) to 5 (out of bounds or net; least accurate) (Hancock and Butler,1995). One Phantom v.41 high speed (500 Hz) video camera was placed on the opposite end to the player to record shuttle landing location for subsequent notation. Each participant took part in an initial warm up with racket and shuttle launcher to familiarise themselves with the testing environment. They then took part in two conditions: *Maximum speed (MS) condition:* the participant was instructed to smash the shuttlecock as fast as possible in the general direction of the target. *Target (TAR) conditio*n: the participant was instructed to smash as fast as possible and aim to hit the centre of the target. Each participant performed 13 forehand smashes in each condition. Racket-shuttlecock marker position data were reconstructed, labelled and gap filled using Vicon Nexus software (Version 2.7.0). Further processing was conducted in MATLAB (2017b) where the curve fitting tool was used to apply a logarithmic curve fitting methodology. This method was previously used for determination of ball release speed during cricket batting (Peploe et al., 2018) and was adapted for the purpose of this study to calculate instantaneous shuttlecock velocity (using all tracked pre and post-impact data) during the forehand smash. All statistical analyses were conducted in IBM Statistics SPSS (V23). An initial exploratory TwoStep cluster analysis (Bayesian information criterion) was performed to identify cluster patterns within the data set.

$$\text{Percentage trade-off} = TAR/MS*100 \qquad (1)$$

The percentage trade-off (Eq. 1) between both the TAR and MS conditions for each participant was calculated for both shuttlecock speed and accuracy score variables. Both variables were then inputted as identification parameters for the cluster analysis. Confirmatory cluster validation procedures were used to check the robustness of the clusters identified. These included a silhouette measure of cohesion and separation (Zhang et al., 2018), leave one out cross-validation method, and two separate one-way MANOVA's for shuttlecock speed and accuracy scores (Ball and Best, 2007; Zhang et al., 2018). Finally, pairwise comparisons were used to compare shuttlecock speed and accuracy score between the identified clusters. An alpha level of 0.05 was used to determine significance.

RESULTS: *Exploratory:* Three cluster groupings with different SATO relationships (Figure 1) were identified, group names were assigned based on terminology used in relation to Fitts' Law (1954) and SATO theory: Fitts' inverse relationship (FIR: n = 16; 31%), No relationship (NR: n = 22; 42%) and Alternate inverse relationship (AIR: n = 14; 27%).

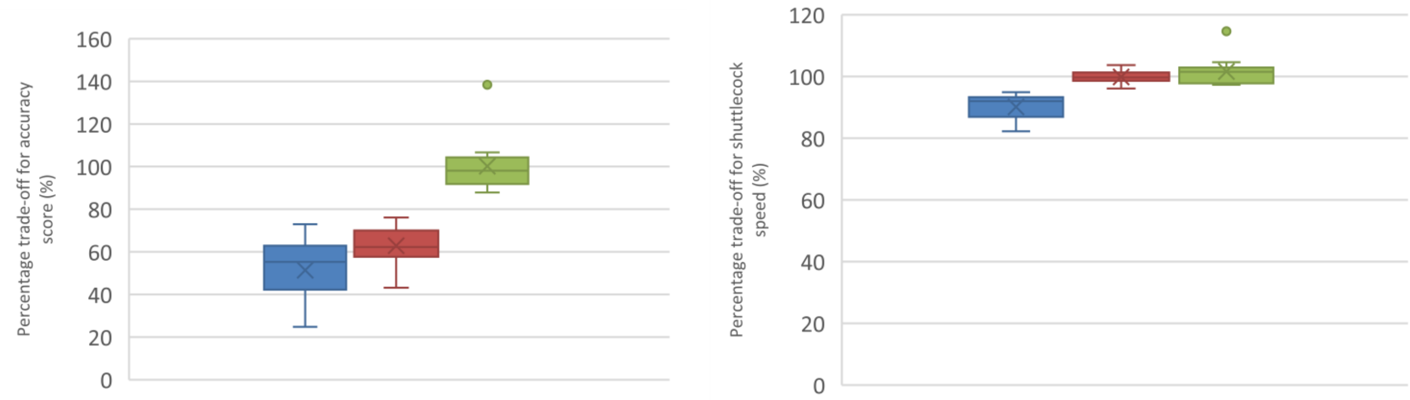

Figure 1. Interquartile range for cluster groups representing the percentage trade-off for shuttlecock speed and accuracy score: *FIR (blue); NR (red); AIR (green)*

Furthermore, percentage trade-off for shuttlecock speed was shown to be the most important predictor (scale of 0-1) of cluster separation in the model with a coefficient of 1. Percentage trade-off for accuracy score resulted in a coefficient of 0.81.

The FIR group reduced shuttlecock speed from the MS condition by 10% and improved spatial accuracy by 49% on average (Table 1).

Table 1. Mean (ME) shuttlecock speed and spatial accuracy for cluster groups

Cluster grouping	Shuttlecock speed	Spatial accuracy
Fitts' Inverse relationship (FIR)	Mean reduction in shuttle speed = min-max= -5%,-18% ME= -10% ± 3.9%	Mean improvement in spatial accuracy=min-max=+27%, +75% ME = +49% ± 14.4%.
No relationship (NR)	Mean reduction in shuttle speed = min-max= -4%, +3% ME= -0.15% ± 2.09	Mean improvement in accuracy = min-max= +24%, +67% ME = +39% ± 7.5
Alternate inverse relationship (AIR)	Mean increase in shuttle speed = min-max = -3%, +14% ME= +2% ± 4.5	Mean decline in accuracy = min-max= -38%, +12%, ME = -0.2% ± 12.6

Confirmatory: Internal validation of the cluster analysis showed that the silhouette measure (scale of -1 to 1; > 0.5 = good fit) of cohesion and separation between clusters had a coefficient of 0.6. This indicated that each object fitted its own cluster well and that there was adequate separation between objects and their clusters (Zhang et al., 2018). Furthermore, the ratio between the largest (NR: n = 22; 42% of participants) and smallest (AIR: n = 14; 27%) cluster was 1.57 indicating that no cluster was more than twice the size of the other (Zhang et al., 2018). The leave one out cross-validation method (Zhang et al., 2018) revealed that 98.1% of grouped cases were correctly classified, with cross-validation showing that only one participant was moved from FIR to the NR group. The two one-way MANOVA's examining the percentage trade-off for shuttlecock speed and accuracy score revealed that all multivariate tests (p < 0.001) were significant. This indicated that the percentage trade-off for shuttlecock speed and accuracy score influenced cluster groupings significantly. Furthermore, tests of between participant effects revealed that the percentage trade-off for shuttlecock speed ($F(2, 49) = 51.879$, $p < 0.001$) and accuracy score ($F(2, 49) = 74.811$, $p < 0.001$) significantly differed between cluster groupings. The percentage trade-off for shuttlecock speed showed a *large* effect size $\omega^2 = 0.55$ and accuracy score presented a *medium* effect size $\omega^2 = 0.09$.
Distinguishing between groupings: Pairwise comparisons for the TAR condition accuracy scores and shuttlecock speed revealed that the FIR group (ME=1.9); 95% CI [1.645, 2.205] were significantly more accurate than the AIR group (ME=2.5); 95% CI [2.236, 2.835] (p = 0.013). Moreover, the NR group (ME=2.0); 95% CI [1.788, 2.266] were significantly more accurate than the AIR group (ME=2.5); 95% CI [2.236, 2.835] (p = 0.031) but were slightly less accurate than the FIR group (NR: ME=2.0 vs FIR: ME=1.9) but not significantly so (p = 1.000). The NR group showed significantly faster shuttlecock speeds (ME=314 $km \cdot h^{-1}$) 95% CI [302, 326] in comparison to both the AIR group (ME=288 $km \cdot h^{-1}$) 95% CI [272, 303], (p = 0.033) and FIR group, (ME=262 $km \cdot h^{-1}$) 95% CI [247, 276] (p < 0.001). Mean shuttle speed was greater for the AIR group (ME = 288 $km \cdot h^{-1}$) in comparison with the FIR group (ME = 262 $km \cdot h^{-1}$) but no significant difference was found (p= 0.056).

DISCUSSION: Three distinct cluster groupings were identified indicating elite badminton players adopt different SATO relationships in order to satisfy spatio-temporal demands. The exploratory and confirmatory cluster analysis represents a robust method for analysing inter-individual SATO relationships, further supporting previous studies using this method (Ball & Best, 2007; Rein et al., 2010; Zhang et al., 2018). Internal validation using the silhouette method showed that the model was a good fit for the data (coefficient of 0.6), moreover cross validation (98.1%) supported the classification membership previously provided by the cluster analysis. The cluster analysis generated three cluster groupings distinguishable by magnitude and direction of relationship. This differs somewhat to previous SATO research investigating sports skills, in that most studies have only compared two pre-determined groupings using a novice-expert paradigm (Tillaar and Ettema, 2006) or compared athletes from different sports

(Freeston and Rooney 2014). Furthermore, this highlights the benefit of using larger sample sizes as it gives a greater observed power (Cohen, 1992). The FIR group utilised the traditional inverse SATO relationship, reported by Fitts' (1954) as being the most effective relationship for satisfying spatial accuracy constraints. It could be argued then that Fitts' (1954) original logarithmic equation is applicable to elite players performing the badminton smash. However, the emergence of the NR group from the cluster analysis contradicts this as they smash faster on average (ME= 314.5 $km \cdot h^{-1}$) than any other group and in doing so achieve a similar level of spatial accuracy to that of the FIR group (NR: ME=2.0 vs FIR: ME=1.9). Results for both the FIR and NR groups are typical of previous findings (Freeston & Rooney, 2014; García et al., 2013) which indicate that 80–99% of maximum speed is the threshold for achieving the highest levels of accuracy, increasing speed over this threshold (AIR) looks to be detrimental to spatial accuracy.

CONCLUSION: Cluster analysis acts as a robust method for identifying inter-individual SATO relationships within a sufficiently sized sample. Badminton coaches should make players aware that by reducing their shuttlecock speed, higher levels of spatial accuracy can be achieved when performing the badminton smash. However, there is still the potential for players to smash close (80-99%) to maximum speed and achieve a similarly high level of spatial accuracy. Further study is needed to establish what SATO relationships are most effective for meeting spatio-temporal demands representative of both singles and doubles competition in badminton.

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ACKNOWLEDGEMENTS: The Badminton World Federation (BWF) for their funding, resources and support of the project.