The impact of physiological load on anticipation skills in badminton: From testing to training

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Abstract

Research remains unclear on the impact of physiological load on perceptual-cognitive skills in sport. Moreover, no study has examined the training of perceptual-cognitive skills under physiological load. The current study comprised two phases. Firstly, we examined the impact of badminton-specific physiological load on anticipatory skills in expert badminton players (n = 13), including key underlying mechanisms, such as gaze behaviour. Under high physiological load, participants displayed less efficient visual search behaviour and showed a reduction in response accuracy. Secondly, we examined the effects of combining perceptual-cognitive simulation training with high physiological load. Ten of the expert badminton players were assigned to a *combined* training group, where the simulation training and the physiological load intervention occurred simultaneously, or an *independent* training group, whereby the two components were completed independently. The *combined* training group showed a positive change in the efficiency of their visual search behaviours compared to the *independent* training group, but no significant performance improvements were found. Overall, findings demonstrate that high physiological load is detrimental to experts' anticipatory skills. However, combining perceptual-cognitive simulation training with high physiological load can potentially negate these debilitating effects.

Keywords: perceptual training; fatigue; visual search behaviour; mental effort

Introduction

High-level sport is characterised by dynamic, uncertain and ever-changing interactions that place severe temporal demands upon athletes (Williams & Ericsson, 2005). Therefore the ability to anticipate the actions of opponents is essential (Alder et al., 2016). Superior anticipatory judgements are underpinned by efficient visual search behaviour (Mann et al., 2007). In badminton, Alder et al. (2014) found that international players utilised a visual search behaviour strategy consisting of fewer fixations of a longer duration compared to their less skilled counterparts. Moreover, the international players fixated on the kinematic locations of their opponent that were most salient for the upcoming shot type and direction (see also, Alder et al., 2016). If efficient visual search behaviours underpin effective anticipation, then threats to the efficiency of visual search behaviour may influence a player's ability to effectively anticipate their opponent's action. During sporting performance the levels of physiological load placed upon athletes is significant. In badminton specifically, for example, research has shown that during match play badminton players operate with an average heart rate of over 90% of the player's maximum (for a review, see Phomsoupha & Laffaye, 2015). It is suggested that success may be in part determined by an athlete's ability to maintain performance under such conditions (Fernandez-Fernandez et al., 2009). While a decline in motor skill caused by high levels of physiological load is well documented (e.g. Lyons et al., 2013), the impact on perceptual-cognitive skill is less clear (Williams et al., 2011).

A recent systematic review showed that the impact of physiological load on an athletes' perceptual-cognitive skills is dependent on the specificity of the induced exercise and the actual perceptual-cognitive task (Schapschröer, Lemez, Baker, & Schorer, 2016). The review highlights that the majority of previous research have either used a 'general' exercise load, such as using a cycle ergometer at moderate or high intensities (e.g. Vickers & Williams, 2007), or a 'general' perceptual-cognitive task such as multiple choice reaction time tasks (e.g.

Lemmink & Visscher, 2005). Of the few that have used a sport-specific exercise load and a sport-specific perceptual-cognitive task, contradictory findings are reported. Royal et al. (2006) tasked skilled water polo athletes with completing a sport-specific physiologically loading protocol followed by a sport-specific decision making test and shooting skill test. The authors describe how ratings of perceived exertion increased across the physiologically loading protocol. Under extreme physiological load, the technical aspect of the players' performance significantly decreased but interestingly the perceptual-cognitive element of performance improved compared to pre-test levels (see also Larkin et al., 2014). However, Casanova et al. (2013) provided contrasting evidence when examining the impact of intermittent exercise on perceptual-cognitive skill, and the underpinning visual search behaviour, of skilled and less-skilled soccer players. The authors report how the intermittent exercise led to a significant decrement in perceptual-cognitive skill in both skilled and less-skilled soccer players. This decrease in perceptual-cognitive skill was accompanied by a reduction in the efficiency of visual search behaviour, as evidenced by an increase in the number of fixations and a decrease in the duration of fixations, in the latter stages of the exercise protocol. Currently these contrasting findings have not been examined further, or linked to a theoretical model, to provide a clear explanation of the impact of physiological load on perceptual-cognitive skills in sport.

The *Integrated Model of Anxiety and Perceptual-Motor Performance* as first presented by Nieuwenhuys and Oudejans (2012), and updated by Nieuwenhuys and Oudejans (2017), offers a range of specific tenets that explain the detrimental effect of anxiety on performance, and may provide a suitable conceptual framework to explore the impact of physiological load on performance. The model proposes that anxiety leads to a reduction in the ability to remain focussed on task-relevant cues and an increase in the potential to be distracted by irrelevant stimuli. Visual search data from Casanova et al. (2013) suggests that under prolonged physiological load participants became less goal-directed. Instead, participants directed attention to task-irrelevant cues more often, as evidenced by an increase in the number, and the shortening, of fixations. This reduction in goal-directed behaviour was accompanied by a decrease in anticipation accuracy, as predicted by the model (Nieuwenhuys & Oudejans, 2012; 2017). The model also suggests that in order for effectiveness of performance to be maintained, individuals can increase mental effort. The additional resource may be directed to the reinforcement of goal-directed attentional strategies (Vine et al., 2013) and/or utilised to ensure pertinent information is extracted from the performance environment. Such explanations, may account for the observed resilience of skilled water polar player's perceptual-cognitive skill to extreme physiological load (Royal et al., 2006; see also, McMorris & Graydon, 2000). However, without a direct measure of attentional control (i.e. visual search behaviour; Alder et al., 2018), this is an assumption that requires investigating.

As factors, such as anxiety and physiological load, may have a debilitating effect on perceptual-cognitive skill in sport, researchers have designed and tested interventions that purposefully and acutely induce these factors during practice to better prepare performers for the rigours of competition (Alder et al., 2016; Nieuwenhuys & Oudejans, 2011; Oudejans & Pijpers, 2009). The model by Nieuwenhuys and Oudejans (2012; 2017) argues that such training may acclimatize players to common competition conditions resulting in greater performance when later exposed to these conditions. This links to the notion of specificity and the idea that learners develop skills that factor in the constraints imposed by the training environment (Barnett et al., 1973; Proteau, 1992). If the constraints in training are representative of competition, then training gains are seen, but if or when the constraints are different, players may struggle to adapt (Lawrence et al., 2014). Specifically, it has been argued that perceptual-cognitive training in the presence of debilitating factors may help players to maintain an efficient visual search strategy whereby attention on information rich areas of the visual display is sustained (Alder et al., 2016). At this point, there is relatively little research examining the impact of physiological load on perceptual-cognitive performance and visual search behaviour, and no research has examined the effect of combining perceptual-cognitive simulation training with high physiological load.

Therefore, this study was composed of two phases. Firstly, we examined the impact of badminton-specific physiological load on anticipation skills, visual search behaviour and mental effort in a badminton-specific video simulation task. The aim was to test the tenets of the *Integrated Model of Anxiety and Perceptual-Motor Performance* as presented by Nieuwenhuys and Oudejans (2012; 2017). We predicted that increasing physiological demands would be accompanied by an increase in mental effort and decrease in the efficiency of visual search behaviour, which at some point would no longer result in effective perceptual-cognitive outcomes (Alder et al., 2016).

The second phase was to examine the effects of combining perceptual-cognitive simulation training with high physiological load. The *Integrated Model of Anxiety and Perceptual-Motor Performance* (Nieuwenhuys & Oudejans, 2012; 2017) was again used as a framework to articulate findings. We predicted that participants who completed the perceptual-cognitive simulation training at the same time as being physiologically loaded would be better able to maintain performance when high physiologically load conditions were reintroduced compared to athletes that completed perceptual-cognitive training without physiologic load (Lawrence et al., 2014). Moreover, it was predicted that any maintenance in perceptual-cognitive skill would be accompanied by participants exerting additional effort to maintain efficient goal-directed visual search behaviour.

Method

Participants

Thirteen expert badminton players (M_{age} = 24.1 years, *Range* 19 – 37 *years SD* = 5.5,) participated. The sample consisted of two athletes who had competed at commonwealth games, three athletes who had competed at international level, six athletes who had competed at national level and two athletes who had competed at county level. At the time of data collection, each player was taking part in at least 10 hr a week of badminton practice, had on average 10 years of competitive experience (*Range* 6 – 20 years, *SD* = 3.9) and played county standard or above for a minimum of five years.

Experimental design

Phase 1: The effect of physiological load on perceptual-cognitive performance

Players were shown video footage of overhead smash shots and asked to anticipate the end-location of the shuttle (6-choice: deep left, deep centre, deep right, short left, short centre, short right). The footage showed a badminton player from a first-person perspective and was occluded 40 ms prior to shuttle/racket contact. Four high-level badminton players (*M* age = 25.3 years, SD = 6.2; *M* = experience = 9.7 years, SD = 3.4) were used to create the stimuli. To provide the most representative view of the shots, the test film was back projected onto a large two-dimensional screen (size: 2.74 m high × 3.66 m wide; Draper, USA) that was positioned on the opposite side of a full-sized badminton court to the player, 1.98 m from the net. Players carried out a shadow shot, accompanied by verbal confirmation, to indicate the anticipated end location of each shot. No feedback was provided. Forty-eight shots were shown in total across six blocks of eight trials with each block separated by one minutes rest. Prior to every trial, players completed a badminton-specific exercise protocol (see figure 1; replicated from Bottoms et al., 2012). The protocol was completed on the badminton court and featured badminton-specific movements and exercise intensities (approximately 83% of maximum heart rate) that simulated the physiological demands of a competitive match play rally (please see supplementary material for further details regarding the protocol).

Phase 2: Examining the effectiveness of training perceptual-cognitive skill under high physiological load

Ten of the 13 players who completed phase 1 volunteered for the training intervention phase of the study. The players were randomly assigned to either a *combined training* group (N = 5, M_{age} = 25.4, SD = 7.2, $M_{\textit{years' experience}}$ = 12.2,) or an *independent training* (N = 5, M_{age} = 21.2, SD = 1.6, $M_{\textit{years' experience}}$ = 8.4, SD = 3.8) group[1]. All participants completed three training sessions on three separate days with a minimum of two and maximum of three days between training sessions. Prior to starting each training session, participants in the combined training group completed a badminton-specific warm up protocol to reach 85% of their predicted maximum heart rate (220-age). Participants then completed three blocks of eight training trials (N = 24 total training trials) of the video-based task they had previously performed; however, during training players received feedback following their response in the form of the clip being replayed without occlusion. Throughout training participants completed the badminton-specific exercise protocol prior to each trial, which did not commence until the participants' heart rate was above 85% of their predicted maximum heart rate. If at any time heart rate dropped below 85% predicted maximum, players were asked to complete another badminton-specific exercise protocol before completing the anticipation trial. This is, the training replicated the physiological demands of the final test block in phase 1 (i.e. high physiological demands).

Participants in the independent training group also completed 24 trials of the video-based training and an equivalent number of repetitions of the exercise protocol (players were

[1] No significant between training condition differences for age, t (8) = 1.44, p = .19, or playing experience, t (8) = 1.75, p = .12.

yoked with counterparts in the combined training group), but crucially not together – that is, the video clips were not interspersed with completion of the exercise protocol. Video-based training and the completion of the set of exercise protocols took place on separate days; that is, participants in the independent training group completed six separate sessions.

All participants completed a post-training anticipation test seven days after the final training session that was conducted in an identical manner to phase 1 of the study.

Dependent Variables

Measures of Physiological load

Heart rate (HR). Players were fitted with a polar heart rate monitor (Polar Electro, Finland) and HR values were recorded immediately after each shuttle of the exercise protocol. Mean HR was calculated for each test block.

Rating of Perceived Exertion (RPE). Immediately after each trial, players rated how hard they felt their body was working using the validated Borg Scale (6 = no exertion at all to 20 = maximal exertion: Borg, 1998). Mean RPE was calculated for each test block.

Performance Effectiveness

A response was correct if it matched the actual end-location of the shuttle in the test film. Response accuracy was calculated as a percentage for each block of eight trials with 16.67% representing chance level performance (6-choice task).

Measures of perceptual-cognitive processing

Rating Scale Mental Effort (RSME). Immediately after each trial, players indicated how much perceived mental effort was needed to complete the task using the validated 0-150 point RSME (2 = no effort to 113 = extreme effort; Zijlstra, 1993). Mean RSME was calculated for each test block

Visual Search Behaviour. Players were fitted with a head-mounted, binocular mobile eye-tracking system (Tobii Pro Glasses 2, Tobii Pro), which computes point of gaze within a scene by calculating the vector between the pupil and the cornea. The system was calibrated using the standard procedure and calibration checks were conducted between test blocks. Eye movement data were recorded at 25 frames per second and analysed frame by frame using video-editing software (Adobe Premier Pro Video Editing Software, Version CS 5, San Jose, USA). Two measures of visual search behaviour were calculated per trial: number of fixations and fixation duration (Abernethy & Russell, 1987; Alder et al., 2014; 2016). A fixation was defined as gaze remaining within three degrees of visual angle of a location or moving object for a minimum duration of 120 ms (Vickers, 1996). Furthermore, we calculated the scan ratio (i.e., a measure of search rate) by dividing the number of fixations by the total durations for each trial (as per Nibbeling et al., 2012). An increase in scan ratio represents less efficient visual search behaviours.

Statistical Analysis

*Phase 1**:** The effect of physiological load on anticipation skills*

Tests of normality using Shapiro-Wilk statistics indicated that parametric analyses were appropriate for each of the dependent variables, with the exception of the measure of perceived exertion which tended to be negatively skewed. Analysis of variance (ANOVA) with repeated measures tested the effect of test block for all other dependent variables with alpha set at $p < .05$ and Bonferroni adjustments for follow-up pairwise comparisons. The non-parametric Friedman test was the preferred non-parametric equivalent to ANOVA. Wilcoxon signed-rank tests were computed to follow-up significant effects with per-contrast alpha adjusted to $p = .0033$ (.05/15) (Steiner & Norman, 2011). For the purpose of clarity, only significant differences and/or large effect size estimates ($r \geq .50$, Cohen, 1988) are reported.

Phase 2: Examining the effectiveness of training anticipation under high physiological load

A preliminary non-parametric analysis of the two training groups' pre-training anticipation test data (Phase 1) found a single significant difference (i.e., performance accuracy of the third test block, $U = 3.00$, $p = .04$) in the six test block comparisons. This was calculated for each dependent variable (all other p's $> .05$). As a result, the decision was made to test for differences in the two groups' response to training by comparing the post-training anticipation test data of the two groups. Shapiro-Wilk statistics indicated that Mann-Whitney U was appropriate for all post-training test comparisons. Again, per-contrast alpha was adjusted to $p = .0083$ to deal with multiplicity (Steiner & Norman, 2011). Effect sizes were estimated using the r conversion formula (Cohen, 1988).

Results

Phase 1: The effect of physiological load on anticipation skills

Measures of physiological load

Heart Rate (HR). A significant main effect of test block was evident, F (2, 22) = 8.59, $p = .002$, $\eta_p^2 = .44$. Heart rates were only significantly higher in the fifth and the final test blocks than in the first test block (p = .03 & .01, r = .80 & .77, respectively); however, large effect sizes were estimated for most comparisons ($r > .50$ with the exception of test block 2 and blocks 3 & 4; test block 3 and block 4; and test block 6 and blocks 4 & 5, see Table 1).

Rating of Perceived Exertion (RPE). A Friedman test found a significant effect of test block, χ^2 (5) = 41.10, $p < .001$. Follow-up Wilcoxon signed-rank tests found significant differences between the fifth test block and all other test blocks (all Zs > -2.94, p's $< .0033$), except the final test block ($p = .26$). Comparisons of the final test block and test blocks one through four, approached significance (p's $\leq .0033$). Again, large effect sizes were found for the majority of comparisons ($r > .50$ with the exception of comparisons between test block 3 and blocks 2 & 4; and between test block 5 and test block 6). In all cases, RPE was higher at points later in the test (see Table 1).

Rating Scale Mental Effort (RSME)

A significant main effect of test block was evident, F (2, 23) = 10.74, p = .001, η_p^2 = .47), which was explained by significant differences in the ratings of mental effort in the first test block compared to the second (p = .003), fifth (p = .006) and final (p = .03) blocks, as well as differences in ratings between the third and fifth test blocks (p = .03). Large effect sizes were estimated for differences between the first test block and the five subsequent blocks; the fifth test block and the four preceding blocks; and the final test block and the first three test blocks (*r's* > .50). Higher ratings tended to be reported later on in the test (see Table 1)

Performance Effectiveness

Figure 2 shows a change in percentage accuracy across the test that was significant, F (5, 60) = 6.08, p = .002, η_p^2 = .34. Response accuracy in the final test block was significantly lower than in both the third (p = .006, r > .81) and the fifth (p = .03, r > .75) block of the test; the difference between the fourth and the final test block approached significance (p = .06, r > .71). Effect size estimations were large for differences between the final test block and each of the five preceding blocks (*r's* > .50). Furthermore, one-sample t-tests found that the final test block was the only example of no better than chance performance, t (12) = 1.34, p = .20, r = .36 (all other (*p's* < .0083, *r's* > .50). Finally, the observable increase in percentage accuracy in the third and fourth test block was supported by large effect size estimates (r > .50, between test block 1 and blocks 3 & 4; and between test block 2 and block 3).

Scan Ratio. A significant main effect of test block was evident for the scan ratio data, F *(3,33)* = 21.36, p < .001, η_p^2 = .64. Follow-up comparisons showed significant differences (all *p's* < .05, *r's* > .70) between the final test block and the preceding five blocks; between the fifth test block and blocks one through three; and when the first and the third block were compared. Figure 3 illustrates an observable trend for an increase in scan ratio as time on task accumulates, which was supported by large effect size estimates for the majority of comparisons ($r > .50$, with the exception of comparisons between test block 2 and blocks 1, 3 & 4; and between test block 3 and test block 4).

Phase 2: Examining the effectiveness of training anticipation under high physiological load

The HR recorded by the two training groups was not significantly different in any of the six test blocks (all U's ≥ 5.50, p's $> .14$, r's $< .47$). Likewise, both the rating of perceived exertion and the rating of mental effort reported by the two training groups were not significantly different in any of the six test blocks (all U's ≥ 4.00, p's $> .07$, r's $< .57$ & all U's ≥ 6.00, p's $> .17$, r's $< .43$, respectively).

The analysis of both performance effectiveness and visual search behaviour are reported in Table 2. The analysis found that the response accuracy of the combined training group was significantly higher than the independent training group in the final test block only. This effect was accompanied by a marginally significant difference in scan ratio, with the scan ratio of the combined training group lower than the independent training group. Furthermore, observation of scan ratio effect sizes suggests that disparity between the training groups widens as time on task accumulates, probably because of the relatively stable scan ratios displayed by the combined training group.

Discussion

Research examining perceptual-cognitive skills in sport have focused primarily on the impact of anxiety on processing efficiency and performance effectiveness (Nieuwenhuys & Oudejans, 2012; 2017). Less attention in the literature has been paid on the impact of another key and potentially debilitating factor, physiological load.

In the first phase of the study, we examined the impact of progressively increasing physiological load on effectiveness and efficiency of anticipation skills in badminton. We predicted that an increase in physiological load would be accompanied by an increase in mental effort and decrease in the efficiency of visual search behaviour (Casanova et al., 2013), which at some point would no longer be accompanied by effective perceptual-cognitive outcomes (Alder et al., 2016). In support of these predictions, performance (response accuracy) was maintained across the first five test blocks, but then fell to no better than chance levels when the physiological load was at its greatest in the sixth and final block. The response accuracy findings across the six test blocks were accompanied by a steady increase in both ratings of mental effort and scan ratio (higher number and/or shorter duration of fixations) as physiological load increased. The pattern of findings is in keeping with the integrated model of the anxiety-performance relationship proposed by Nieuwenhuys & Oudejans (2012; 2017). The model predicts that situational factors induce mental effort in attempt made by the performer to maintain performance effectiveness. The additional resource may be used to enforce goal-directed processing and/or maintain effective visual search behaviour (Vine et al., 2013). In this case, the efficiency of visual search behaviour was compromised by the increase in physiological load, but this was not accompanied by a meaningful drop in performance until the later stages of the test when physiological load was highest (Casanova et al., 2013).

The current data contradict findings that imply perceptual-cognitive skills are actually enhanced by high physiological loads (Royal et al., 2006). While there was a trend for a response accuracy increase with sustained physiological load in the current study (see Figure 2), this did not appear significant. One explanation for the divergent findings is that Royal et al. (2006) required participants to make a tactical decision of *what to do next* rather than to anticipate *what will happen next*. The two perceptual-cognitive skills may place different demands on a player's attentional resources to the extent that the interaction with high physiological load produced very different outcomes. Alternatively, the differential findings may be due to differences in experimental design. Royal et al. (2006) physically exerted water polo players to various degrees before a full block of 10 decision making trials was administered. The decision-making test took approximately four minutes to complete, which afforded participants the opportunity to recover and may have lessened the impact of physiological load. In the current study, participants completed the badminton-specific exercise protocol prior to each anticipation trial, thus dramatically reducing recovery time and closer simulating the sustained physiological load experienced in real-match rallies.

While an attempt was made to replicate the sport-specific physical demands of badminton (Schapschröer et al., 2016), we acknowledge the unsystematic variance introduced by not carefully controlling the physiological load experienced by each individual player (Vickers & Williams, 2007). Furthermore, we did not consider other factors known to impair performance, such as mental fatigue (Smith et al., 2016) or anxiety (Alder et al., 2016). Future research should contemplate the progressive build-up and interaction of known stressors, in order to provide a fuller account of the relationship between physiological load and perceptual-cognitive performance. Likewise, future research should consider the motor component of performance. In order to control visual-perceptual information in the current study, players played a shadow shot rather than perform an interceptive action. Re-establishing the coupling of perception and action may modify the perceptual information used to anticipate an opponent's action (Fajen, Riley & Turvey, 2008) .Moreover, it may divert attentional resources away from perception of salient cues and/or response selection and towards the control of the motor action, particularly under pressure (Masters, 1992; Masters & Maxwell, 2008) and possibly when experiencing a high physiological load (Poolton, Masters & Maxwell, 2007). A holistic understanding of the impact of physiological load on sport performance will allow for the effective design of targeted training interventions.

In the second phase of the study, we examined the effects of combining perceptual-cognitive simulation training with high physiological load similar to that induced in phase 1 of this study, which was shown to be debilitative to both processing efficiency and performance effectiveness. We predicted that training anticipation under such conditions would better prepare players for later exposure to high physiological load (Alder et al., 2016; Lawrence et al., 2014). The results provided partial support for our hypothesis. Positive changes to the efficiency of visual search behaviour following training were observed. Combined training appeared to counteract the gradual reduction in visual search efficiency evident in phase 1 (see Figure 3); particularly, when the physiological load reached the high level experienced throughout training. This was in contrast to a negligible effect on visual search efficiency of perceptual-cognitive simulation training independent of physiological load. However, contrary to our predictions improved efficiency of visual search was not accompanied by statistically significant advancements in performance effectiveness perhaps due to increased effort on the task (Nieuwenhuys & Oudejans, 2012; 2017).

Alder et al. (2016) speculated that opportunities to acclimatize to the conditions that accompany performance, in this case high physiological load, may have a positive adaptive effect on visual attentional processes and subsequent performance. In the current study, the combined training intervention was designed to replicate the heart rate and perceived exertion that had a debilitative effect on performance effectiveness in block six of phase 1. It appears that players acclimatized to the constraints imposed by the intervention and adapted their visual search behaviour accordingly. However, the adaptations made did not afford significant improvements to the efficiency of visual search behaviour when physiological load was lower than experienced in training; that is, effects seemed specific to the targeted level of physiological load. The findings, therefore, show some support for the specificity of learning hypothesis (Barnett et al., 1973; Proteau, 1992), which argues that learners develop skills that factor in the constraints imposed by the training environment. The current findings support the notion of specificity in such that changes in effective visual search behaviour are found if the constraints of training match those of performance; once the constraints change (i.e. low physiological load) the significant changes do not necessary transfer (Lawrence et al., 2014). This highlights the importance of understanding the physiological load that occur in competition and replicating them as closely as possible in training.

This may not just concern physiological load but also mental fatigue, which has been shown to impair physical and technical performance in sport (Smith et al., 2016). Future research should examine the progressive build-up, and coupling, of physiological load and anxiety across competition. Once this is understood then attempts can be made to examine the impact of these factors on both motor skills and perceptual-cognitive skills combined, and whether integrating these conditions in to training programs has a positive impact on subsequent performance.

A true test of the effectiveness of training perceptual-cognitive skill under high physiological load would be the extent that any positive effects transferred to real match-play (Broadbent et al., 2014). In an ideal world, performance analysis of competitive match play would provide markers of anticipatory skill (e.g. Triolet, Benguigui, Runigo & Williams, 2013), such as movement time of the participant in relation to shuttle-racket contact point of the opponent, which would be indicative of performance gains. However, closer examination of underlying mechanisms such as visual search behaviour would require the use of eye tracking technology in a match setting and would be limited by calibration issues and could also act as a distraction for players not used to playing in glasses. It would also have been desirable to include a control and/or placebo sample group, in order to better isolate the relative effects of the Combined and the Independent training interventions (Combined and Independent). However, the differences found between the two experimental groups imply, at the very least, that training anticipation under high physiological load increases the resilience of visual search behaviour to heightened physiological load compared to training anticipation without a load. The absence of a control group was due to the reduced size of this specialised high-performance population. The small sample size also compromised our approach to data analysis and may have hidden interesting effects or, alternatively, found effects that are not generalisable. A replication study is needed to verify the insight gained from this small, highly skilled sample.

To conclude, from an applied perspective this study poses a problem – cumulative physiological load negatively impacts the processing efficiency (mental effort and visual search behaviour) and performance effectiveness of perceptual-cognitive skills – and provides a solution - design learning environments that replicate the physical demands of competition (Nieuwenhuys & Oudejans, 2012; 2017). Therefore, practitioners might deliberately and progressively increase the level of physiological load across a practice session in order for it to replicate the length and intensity of a competitive match. On face value, physiological load is considerably easier for practitioners to manipulate (and monitor) than sport-specific mental fatigue and anxiety. That being said, it may be found to be important to consider the interaction of common stressors in the design of practices that best prepare players for competition.

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