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Mental fatigue impairs visuomotor response time in badminton players and controls

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ABSTRACT

Purpose: It has recently been reported that professional road cyclists have superior inhibitory control and resistance to mental fatigue compared to recreational cyclists. We sought to assess whether badminton players also have superior executive functions and whether they are more resistant to mental fatigue than controls on a visuomotor task.

Methods: Eleven healthy controls (mean ± SD; age: 25 ± 4y; 6 females, 5 males) and nine healthy badminton players (age: 23 ± 3y; 4 females, 5 males) performed two experimental trials in a randomized crossover order. Participants completed a baseline visuomotor task, followed by a Flanker task. Next, they performed either a 90-min Stroop task (MF) or watched a 90-min documentary (CON). Immediately thereafter, the Flanker task and the visuomotor task were completed again. Multiple physiological and psychological measures were assessed during the protocol.

Results: Badminton players' and controls' accuracy during the Stroop task decreased over time ($p = 0.023$). Subjectively, both groups perceived the Stroop task as more mentally demanding than the documentary ($p < 0.001$). In addition, higher mental fatigue was perceived in MF compared to CON, independently from group ($p = 0.029$). In the visuomotor task, controls as well as badminton players reacted significantly slower to the complex stimuli when mentally fatigued (~7%; $p < 0.001$). Badminton players (1109 ± 251 ms) outperformed controls (1299 ± 227 ms; $p = 0.022$) in the visuomotor task. However, this was not the case in the Stroop and Flanker task; in terms of accuracy and response time, badminton players and controls performed similarly.

Conclusion: These findings provide evidence that badminton players have better visuomotor response time than controls. However, they do not seem to be more resistant to the negative effects of mental fatigue on open skill-visuomotor performance. Furthermore, our study suggests that cognitive tasks with a larger motor component, such as our visuomotor task, are more sensitive to the negative effects of mental fatigue than traditional cognitive tasks (e.g. Flanker task) that have a very small motor component.

1. Introduction

Mental fatigue can impair multiple visuomotor related skills in sport-specific (Duncan, Fowler, George, Joyce, & Hankey, 2015; Le Mansec, Pageaux, Nordez, Dorel, & Jubeau, 2017; Smith et al., 2016; Veness, Patterson, Jeffries, & Waldron, 2017) and non-sport-specific settings (Behrens et al., 2017; Lew & Qu, 2014). In addition, Smith et al. (2016), Le Mansec et al. (2017) and Veness et al. (2017) observed that also within trained (ranging from moderately trained to elite) athletes mental fatigue has a negative effect on sport-specific visuomotor related skills. For example, Smith et al. (2016) used the Loughborough Soccer Passing and Shooting Test with experienced soccer players and found that their shot speed and accuracy decreased when mentally fatigued. Similarly, Le Mansec et al. (2017) found that ball speed decreased and number of faults increased in mentally fatigued table tennis players who play at regional-national level in France.

These findings are in accordance with the effect of mental fatigue on endurance performance in endurance trained athletes (Van Cutsem, Marcora, et al., 2017). Based on these results, one would conclude trained/elite athletes are not immune to mental fatigue-induced

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impairments in sport performance. However, given the cross-over nature of all these studies, we should be careful whilst drawing conclusions. Trained/elite athletes might still be more resistant to mental fatigue than untrained individuals. In literature it has already been suggested that genetic and/or environmental (i.e. training effects) factors could underlie an athlete's greater resistance to mental fatigue-associated physical performance impairments (Martin et al., 2016). Evaluating whether athletic status moderates the resistance to mental fatigue is of importance. On the one hand, it allows to determine the factors that may contribute to successful sport performance, while on the other hand it provides further insights to the mechanisms underlying the detrimental effect of mental fatigue on sport performance.

In endurance sport, Martin et al. (2016) was the first to design a study to specifically assess whether a certain level of training had any influence on the effect of mental fatigue. Interestingly, they found that professional cyclists exhibited superior performance during a 30-min Stroop task compared to recreational cyclists, which is indicative of stronger inhibitory control. Moreover, professional cyclists displayed a greater resistance to the negative effects of mental fatigue on a 20-min cycling time trial compared to recreational cyclists (Martin et al., 2016). Following this first study, Clark et al. (2019) also attempted to determine whether athletic status influences the effect of mental fatigue on cycling performance. Clark et al. (2019) found that a 6-min cycling time trial performance in both untrained men and non-professional highly trained individuals with a history of competition in a variety of sports was unaffected by mental fatigue. Unfortunately, as in the study of Martin et al. (2016), a similar 30-min prolonged cognitive task was used to induce mental fatigue. The choice for a rather short mentally fatiguing task (i.e. in mental fatigue-literature tasks of 90 min or more are often used (Van Cutsem, Marcora, et al., 2017)) in the study of Clark et al. (2019) might explain why they were not able to observe changes in multiple markers of mental fatigue. Clark et al. (2019) did not find any decline in performance during the prolonged cognitive task, nor an increase in subjective mental fatigue post the cognitive task. In addition, a mental fatigue-associated drop in frontal cortex oxygenation (i.e. a drop in $\Delta[HbO_2]$ (Ahn, Nguyen, Jang, Kim, & Jun 2016; Li et al., 2009)) was not observed. As such, Clark and colleagues themselves express their uncertainty whether they were successful in inducing mental fatigue in the first place (Clark et al., 2019). This is a limitation that is also put forward in the study of Martin et al. (2016), and that might be caused by the relatively short period of increased mental load. The duration of the mental load is thought to be an important factor to successfully induce mental fatigue (Van Cutsem, Marcora, et al., 2017). In their systematic review on mental fatigue and physical performance, Van Cutsem, Marcora, et al. (2017) already argued that at least 30 min of mental load is necessary to result in mental fatigue and that longer tasks appear to induce more severe mental fatigue. Moreover, a recent study by Fortes et al. (2019) also appears to support this statement. Fortes et al. (2019) observed that 30 min and 45 min, but not 15 min, of smartphone use impaired decision-making during a soccer game in soccer athletes.

Apart from the discussion whether both Martin et al. (2016) and Clark et al. (2019) did succeed in inducing mental fatigue, the role of training level in moderating the effect of mental fatigue on endurance performance suggested by Martin et al. (2016) does not seem to be confirmed by the study of Clark et al. (2019). This discrepant outcome could be due to the fact that Clark et al. (2019) used a 6-min preload (i.e. a constant work rate-part) followed by a 6-min high intensity time trial to assess endurance performance. This preload may have had a restorative effect on the mental fatigue state (Van Cutsem, De Pauw, Buyse, et al., 2017). A second potential reason why the study of Clark et al. (2019) could not confirm the results of Martin et al. (2016) is that the genetic and/or environmental factors that are put forward by Martin et al. (2016), are in fact not moderating factors of this mental fatigue-effect. Clearly more research is necessary on this topic.

Therefore, we sought to assess whether open skill-athletes (i.e. required to react in a dynamically changing, unpredictable and externally-paced environment) might, like cyclists, be more resistant to mental fatigue than untrained individuals (i.e. controls). In order to do so, the effect of a 90-min mentally fatiguing task on an open skill-visuomotor task (visuomotor task; i.e. a test where a lunge movement combined with an arm extension is required) was examined in both badminton players and controls. Several studies demonstrated that sport-specific visuomotor related skills are impaired in trained athletes when mentally fatigued (Le Mansec et al., 2017; Smith et al., 2016; Veness et al., 2017). However, it is still plausible that visuomotor performance in trained athletes is less affected by mental fatigue. Most of the genetic and/or environmental (e.g. the lifestyle of professional athletes) factors that are put forward by Martin et al. (2016) to increase the resistance to mental fatigue in endurance athletes also apply to other types of athletes (e.g. open skill). Subsequently, these factors could cause open skill athletes to be more mental fatigue-resistant as well. We hypothesized that mental fatigue would negatively affect performance on the visuomotor task in controls, while badminton players would demonstrate greater resistance and be less/not affected by mental fatigue (Martin et al., 2016). In addition it was expected that badminton players would outperform controls on the visuomotor task as well as on the Stroop task (Martin et al., 2016).

2. Methods

2.1. Participants and ethical approval

An a priori sample size calculation based on the results reported in the study of Martin et al. (2016) (reported effect size of the interaction between condition and group was $\eta_p^2 = 0.293$) revealed – with α set at 0.05 and an actual power of 0.85 – that a total of 8 participants were needed in each group to observe a similar interaction effect. Twelve healthy controls and ten healthy badminton players volunteered to participate in this study, and eventually, eleven healthy controls (mean ± SD; age: 25 ± 4 y, stature: 1.69 ± 0.07 m, body mass: 70.2 ± 13.8 kg, 6 females, 5 males) and nine healthy badminton players (mean ± SD; age: 23 ± 3 y, stature: 1.73 ± 0.11 m, body mass: 67.0 ± 12.8 kg; 4 females, 5 males) were included in the data analysis (see *Results* for reason of dropout). Each participant gave a written informed consent prior to the study and were naive of its aims and hypotheses. Controls were not engaged in any kind of regular physical activity during the last 5 years, badminton players competed at national and/or international level and performed ≥2/3 badminton training sessions per week and had ≥8 years badminton experience. The experimental protocol and procedures were approved by the Research Council of the Vrije Universiteit Brussel, Belgium. The participants were instructed to sleep a similar amount of time before each trial (at least 7 h), refrain from the consumption of caffeine and alcohol and to avoid vigorous physical activity the day before and the day of each visit. In addition, participants were asked to have the same meal the morning of each trial. The use of any kind of medicinal products during and between the trials was prohibited. If participants could not meet these standards, they were excluded from the study.

2.2. Experimental protocol

Participants were asked to report to the lab for 3 consecutive trials, which were all conducted at the same time of day (in the morning) and were separated by at least 3 days to ensure full recovery. The first trial was a familiarization trial, followed by an experimental trial (MF) and a control trial (CON). All trials were conducted in thermoneutral conditions (23.5 °C, humidity 35%) and took ~2 h to complete. MF and CON were completed in a randomized, crossover manner (see Fig.1 for a complete overview and timeline of the protocol). Participants had to perform a baseline visuomotor task (see *visuomotor task*), followed by a Flanker task (see *Flanker task*). Next, they performed either a 90-min

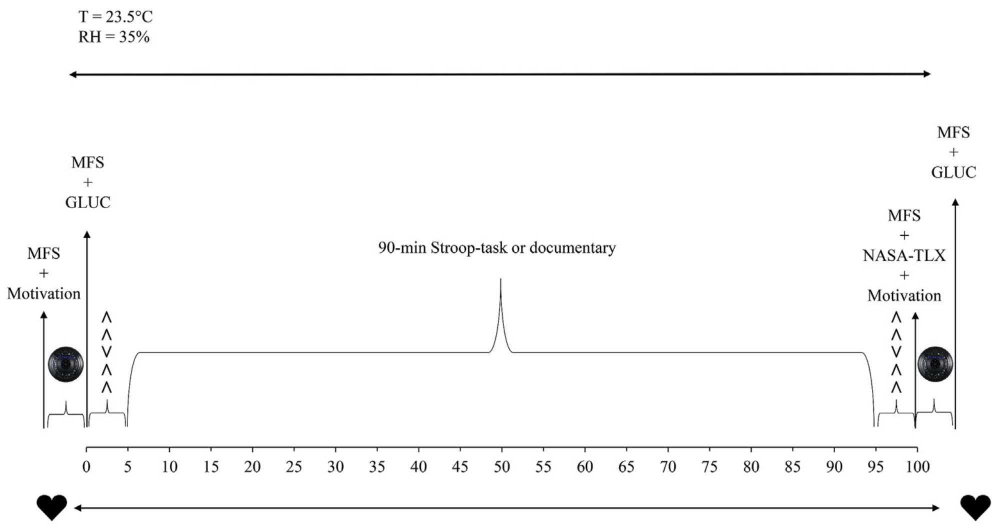

Fig. 1. Protocol timeline (min; x-axis). First of all, participants had to perform a visuomotor task. After completing the baseline visuomotor task, participants sat down and completed a 90-min mentally fatiguing task or a 90-min control task, that was preceded and immediately followed by a 3-min Flanker task. Immediately (~2 min) after the second Flanker task a second visuomotor task was performed. T = ambient temperature; RH = relative humidity; MFS = self-reported mental fatigue; Motivation = success motivation and intrinsic motivation scales developed and validated by Matthews et al. [18]; NASA-TLX = the National Aeronautics and Space Administration Task Load Index; GLUC = blood glucose; ♥ = heart rate; = visuomotor task; ∧∧∨∧∧ = 3-min Flanker task.

Stroop task (MF; see *mental fatigue task*) or watched a 90-min documentary (CON; see *control task*). Immediately thereafter, the Flanker task and the visuomotor task were completed again. In the familiarization trial participants completed all procedures as if it was an experimental trial (see Fig. 1), except for the 90-min cognitive task. Instead of the 90-min cognitive task, participants performed a 30-min version of the Stroop task to familiarize with all instructions.

Visuomotor task To develop a visuomotor task, Fitlight-hardware and software was used (http://www.fitlighttraining.com/). Seven lights were set up against a wall (see Fig.2) and illuminated for 2 s, one after the other in a set sequence. These lights colored, similar to the Stroop-stimuli, red, blue, green or yellow. If a light turned red, green or yellow (i.e. simple stimuli) participants had to put out the light as fast as possible by passing before the light with the left or right hand within a range of 5 cm. However, if a light turned blue (i.e. complex stimulus), participants were instructed not to respond to the stimulus on the wall. Instead they had to turn around and put out another light lying behind them on the floor (1 m 50 cm; see Fig.2). After each stimulus, participants were instructed to return to their starting position indicated on the floor (perpendicular to light no.1, 1 m 20 cm away from the wall

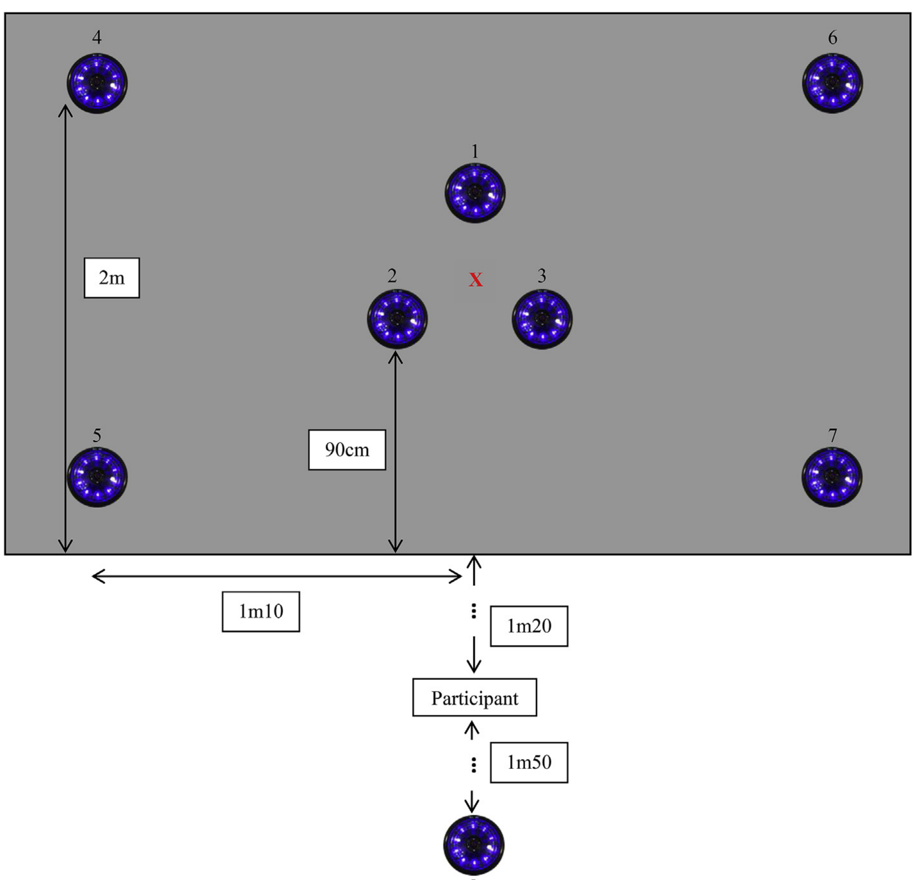

Fig. 2. Overview of the visuomotor task.

and with both feet ~30 cm apart and on the same line), and to focus again on the fixation cross (see Fig. 2). Each color was presented 16 times, yielding a total of 64 stimuli. The sequence in which the colors appeared was programmed randomly (www.randomization.com), as was the location of the light in which the color appeared. The inter-stimulus time varied between 3, 4, 5 or 6 s and each inter-stimulus time was randomly used 16 times. Total task duration was approximately 6 min 30 s. To avoid learning effects each visuomotor task was different as the pre-programmed sequence would always start randomly somewhere within the sequence. Accuracy and response time (RT) for each stimulus-type (complex vs simple stimuli) were calculated based on the data (i.e. a list of accuracy and RT on each stimulus in the visuomotor task) collected by the according software.

Flanker task In the Flanker task participants were instructed to respond as quickly and accurately as possible to the direction of a target arrow while ignoring two flankers on each side (see Van Cutsem et al. (2017) for a detailed description). The task used in the present study only differed from the task used in the study of Van Cutsem, De Pauw, Buyse, et al. (2017) in that sense that all stimuli from the present task were incongruent (e.g., < < > < <), requiring a great level of inhibitory control. The second Flanker task was performed 20 s after completion of the 90-min mentally fatiguing task or control task. To assess performance on the Flanker task accuracy and RT were collected. Participants were excluded from the analysis, based on the assumption that they were already fatigued or not adequately familiarized (Nakagawa et al., 2013), if they were not able to reach a minimum accuracy level of 90% in the first Flanker task (i.e. the baseline performance).

Mental fatigue task A modified Stroop task of 90 min, partitioned in 8 blocks of 252 stimuli (i.e. 10 min 30 sec), was used as the mentally fatiguing task. This 90-min task was continuous with no breaks (i.e. participants had no knowledge of the existence of the 8 task blocks). Participants were instructed to respond as quickly and accurately as possible. The inclusion of the 8 task blocks/epochs allows the researcher to examine performance impairment (i.e. accuracy and RT) as a function of time-on-task which is a behavioral indicator of mental fatigue (Head & Helton, 2012; Van Cutsem, Marcora, et al., 2017). In this task, four colored words ("red", "blue", "green" and "yellow") were presented one at a time on a computer screen. If the ink color of the word was yellow, green or blue the participants were required to indicate the color of the word, ignoring the meaning of the word itself (i.e. 'color' stimuli). If however, the ink color was red, the button to be pressed was the button linked to the real meaning of the word (i.e. 'meaning' stimuli; see Van Cutsem, De Pauw, Marcora, Meeusen, and Roelands (2017) for a detailed description). The display of the word and its ink color were randomly selected by the computer (100% incongruent), with all incongruent word-color combinations being equally common (meaning, in each block 63 words were presented in the color red, yellow, green and blue). Prior to each 90-min Stroop task, time-keeping devices such as watches and cell phones were surrendered and during the task participants did not receive any feedback on performance nor time lapse. Participants were excluded from the analysis if they were not able to reach a minimum accuracy level of 70% in the first or second time interval of the task, based on the assumption that they were already fatigued or not adequately familiarized (Nakagawa et al., 2013).

Control task In the control task participants had to watch a documentary ((A) "Planet earth" (BBC Worldwide, 2006), (B) "When we left earth – the NASA missions" (Discovery entertainment, 2008), and (C) "ooggetuigen" (eyewitnesses): (Ca) "Honden" (Dogs), (Cb) "Haaien" (Sharks), or (Cc) "Vulkanen" (Volcanoe's; BBC Worldwide, 2007)). In order to promote engagement and avoid boredom participants were given the choice: 1 chapter from (A) and 1 disc "ooggetuigen" or 1 disc from (B), for a total of 90 min. These documentaries were chosen based on their emotionally neutral, yet engaging content.

Physiological and subjective measurements During the entire protocol a researcher was sitting behind the participant to ensure compliance with the intervention. Participants were equipped with a heart rate monitor to continuously record heart rate (HR). Blood glucose was measured before the 90-min task and immediately after finishing the second visuomotor task by extracting 0.6 µl of blood from the right earlobe (CONTOUR LINK Medtronic Blood Glucose Meter System, Bayer, Basel, Switzerland). Subjective psychological assessment took place with a mental fatigue-visual analogue scale (MFS) (Lee, Hicks, & Nino-Murcia, 1991), the National Aeronautics and Space Administration Task Load Index (NASA-TLX; Hart (1988)) and the success motivation and intrinsic motivation scales developed and validated by Matthews (2001). The validity and reliability of a visual analogue scale (0–10 cm) to assess fatigue was demonstrated by Lee et al. (1991), MFS asked the participant the question of 'How mentally fatigued do you feel?', and ranged from 'not at all' to 'completely exhausted' (Lee et al., 1991). The NASA-TLX scale assesses subjective workload and was taken after finishing the 90-min task. Motivation related to the visuomotor task was measured by the scales of Matthews (2001) and was assessed before both visuomotor tasks (see Fig.1).

2.3. Statistical analysis

All data are presented as means ± standard deviation (SD) unless stated otherwise. The Shapiro-Wilk test was used to test the normality of the data. If data were not normally distributed (i.e. mean HR, accuracy on the Stroop and Flanker task), a square root transformation was performed in an attempt to achieve a normal distribution. Sphericity was verified by the Mauchly's test. When the assumption of sphericity was not met, the significance of F-ratios was adjusted with the Greenhouse-Geisser procedure.

A two-way mixed (2x2) ANOVA was used to assess the effects of group (badminton players vs controls) and condition (MF vs CON) on each NASA-TLX subscale and on square root transformed mean HR. A three-way mixed ($2 \times 2 \times 2$) ANOVA was used to assess the effects of group, condition and time on intrinsic and success motivation towards both visuomotor tasks. Blood glucose ($2 \times 2 \times 2$) and MFS ($2 \times 2 \times 4$) responses were analyzed with three-way mixed ANOVAs, with factors group, condition and time. A three-way mixed ($2 \times 8 \times 2$) ANOVA was used to test the effect of group (badminton players vs controls), time (first to eighth block) and stimuli (meaning vs color) on RT and square root transformed accuracy (square root transformation was performed after subtracting raw accuracy from 1.1) during the mental fatigue task. Three-way mixed ($2 \times 2 \times 2$) ANOVA was used to test the effects of group, condition and time on RT and square root transformed accuracy during the Flanker tasks (square root transformation was performed after subtracting raw accuracy from 1.1). A four-way mixed (2x2x2x2) ANOVA was used to test the effects of group, condition, time and stimuli (simple vs. complex) on RT during the visuomotor tasks. Wilcoxon signed ranks tests were employed to assess the effect of condition and time on visuomotor task accuracy in each group and each stimulus type.

If significant interaction effects including the factors condition and time in the four-way, three-way or two-way mixed ANOVAs were observed, subsequent three-way or two-way mixed ANOVAs or paired t-tests were performed to elucidate the main effect of condition and time. If no significant interaction effects, including the factors condition and time, in the four-way, three-way or two-way mixed ANOVAs were observed, main effects of condition and time were immediately studied and further interpreted through pairwise comparisons with Bonferroni correction.

In order to assess whether badminton players possess superior inhibitory control and task switching-ability compared to controls, and to control for the potential confounding effect of differences in resistance to mental fatigue, planned comparisons were executed in the first time interval of the Flanker task, Stroop task and visuomotor task.

Significance was set at < 0.05 for all analyses, which were conducted using the Statistical Package for the Social Sciences, version 23

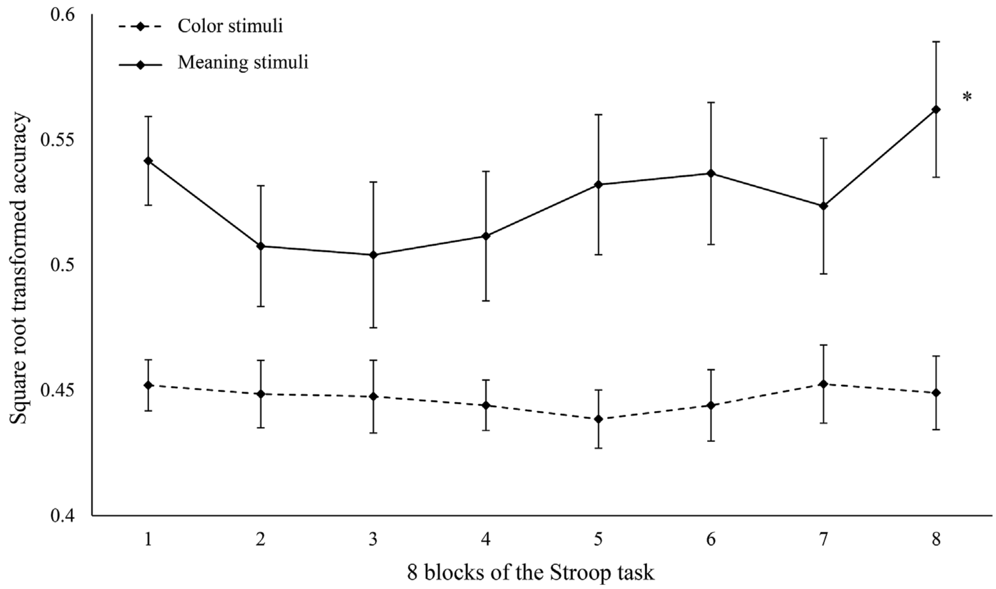

Fig. 3. Square root transformed accuracy during the 8 blocks of the Stroop task (independent of group; n = 20). * denotes a significant main effect of time on the meaning stimuli in both badminton players and controls ($p < 0.05$). Data are presented as means ± SE.

(SPSS Inc., Chicago, IL, USA).

3. Results

3.1. Manipulation checks

All participants except two (1 control and 1 badminton player) reached the required minimum performance level of 70% in one of the two first time intervals during the Stroop task and were included in the data-analysis.

3.1.1. Behavioral

The effect of time on the transformed accuracy-data differed in both types of stimuli (time x stimuli; $F(7,126) = 2.1$; $p = 0.050$), group did however not affect the effect of time. Within the color stimuli, transformed accuracy was similar over time ($F(4.2,79.3) = 0.5$; $p = 0.753$; see Fig. 3). However, an increase in transformed accuracy over time was found within the meaning stimuli (i.e. performance dropped; $F(7,133) = 2.4$; $p = 0.023$; $\eta p^2 = 0.11$; See Fig. 3). In terms of RT it was shown that participants performed faster in time independent of group in both the color stimuli ($F(7,133) = 3.5$; $p = 0.002$; $\eta_p^2 = 0.16$; see Fig. 4) and the meaning stimuli ($F(3.9,74.2) = 12.7$; $p < 0.001$; $\eta_p^2 = 0.4$; see Fig. 4). Regarding transformed accuracy on the Flanker task, no effect of condition, time or group was observed. RT on the Flanker task was observed to increase in time independent of group and condition (PRE: 362 ± 36 ms → POST: 371 ± 35 ms; $F(1,18) = 7.2$; $p = 0.015$; $\eta_p^2 = 0.29$). In addition, the planned comparison in the first time interval of the Stroop task and the first Flanker task demonstrated that there was no difference in accuracy or RT between badminton players and controls in both tasks.

3.1.2. Subjective

Overall subjective mental fatigue was higher ($F(1,18) = 5.6$; $p = 0.029$; $\eta_p^2 = 0.24$) in MF (44 ± 17) compared to CON (38 ± 12), independently from group. Subjective mental fatigue was higher after both the Stroop and control task in comparison to before the respective tasks ($F(3,54) = 34.7$; $p < 0.001$; $\eta_p^2 = 0.66$; pre control and Stroop task = 30 ± 18; post control and Stroop task = 63 ± 17). In both badminton players and controls, the mental demand (MF = 84 ± 17; CON = 54 ± 24), physical demand (MF = 22 ± 21; CON = 11 ± 11), temporal demand (MF = 61 ± 19; CON = 31 ± 26), effort (MF = 65 ± 22; CON = 43 ± 28) and frustration (MF = 64 ± 22; CON = 30 ± 21) subscale of the NASA-TLX were perceived as higher after the Stroop task compared to the control task ($F(1,18) \geq 8.1$; $p \leq 0.011$; $\eta_p^2 \geq 0.41$). Only the performance subscale of the NASA-TLX was not perceived as different between both conditions. No difference was observed in intrinsic and success motivation towards both visuomotor tasks.

3.1.3. Physiological

Transformed mean HR was significantly ($F(1,18) = 8.9$; $p = 0.008$; $\eta_p^2 = 0.33$) higher during the Stroop task (8.8 ± 0.6; absolute value = 77 ± 9 bpm) compared to the HR during the control task (8.5 ± 0.5; 72 ± 9 bpm) independently from group. Blood glucose levels decreased across the duration of the protocol ($F(1,17) = 10.5$; $p = 0.005$; $\eta_p^2 = 0.38$); Starting values of blood glucose were at 93.8 ± 6.7 mg/dl and decreased to values of 86.6 ± 7.6 mg/dl at the end of the protocol. This drop in blood glucose levels in time was unaffected by condition or by group.

3.2. Performance on the visuomotor task

3.2.1. Accuracy

Non-parametric testing showed that there was no effect of condition or time on accuracy.

3.2.2. Response time

The effect of the mentally fatiguing task on RT during the visuomotor task was independent of group. In contrast, the type of stimulus did interact with the effect of condition and time on visuomotor RT (condition x time x stimuli; $F(1,18) = 8.0$; $p = 0.011$). This interaction indicates that the mentally fatiguing task differently affected visuomotor RT for complex and simple stimuli. Follow-up tests in each specific type of stimulus demonstrated that within the complex stimuli an interaction between the effects of condition and time was present (condition x time; $F(1,19) = 10.0$; $p = 0.005$). Participants became significantly slower in time only in MF ($t(19) = -4.4$; $p < 0.001$; $d = 0.98$; PRE: 1282 ± 242 ms; POST: 1372 ± 249 ms; see Fig. 5), while the effect of condition ($t(19) = 2.2$; $p = 0.040$; $d = 0.49$; 1372 ± 249 ms; CON: 1322 ± 253 ms; see Fig. 5) was only present in the second visuomotor task. Within the simple stimuli only a main effect of time ($F(1,19) = 25.9$; $p < 0.001$; $\eta_p^2 = 0.58$) was observed,

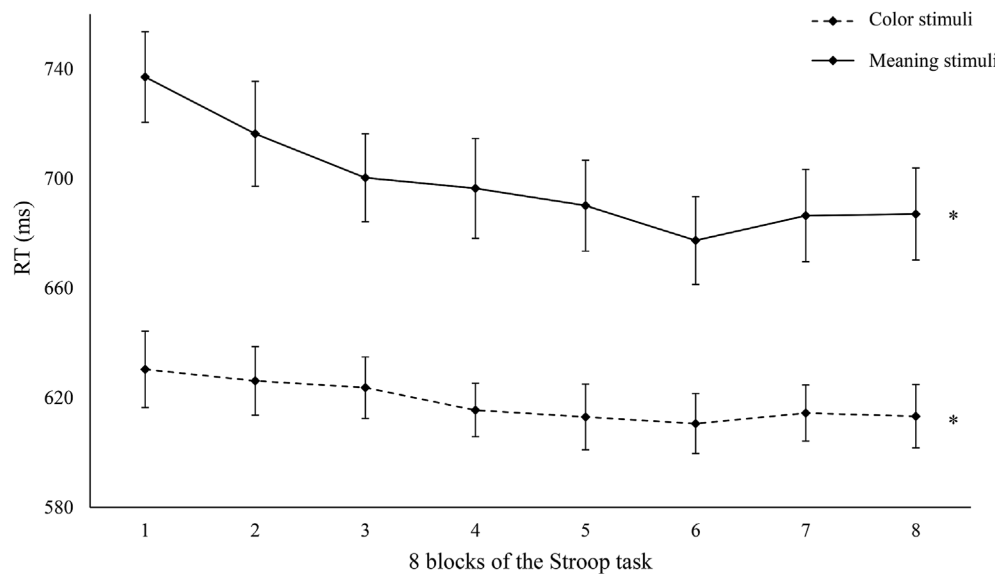

Fig. 4. Response time (RT) during the 8 blocks of the Stroop task (independent of group; n = 20). * denotes a significant main effect of time in both badminton players and controls ($p < 0.05$). Data are presented as means ± SE.

independent of condition.

The planned comparison in the first visuomotor task demonstrated that the controls (1299 ± 227 ms) performed slower than the badminton players (1109 ± 251 ms), independently from stimuli and condition ($F(1,18) = 6.3$; $p = 0.022$; $\eta_p^2 = 0.26$).

4. Discussion

To our knowledge this is the first study that assessed the effect of mental fatigue on open skill-visuomotor performance in badminton players and controls. The most important findings were: (I) Badminton players demonstrated a superior visuomotor performance compared to controls; (II) Mental fatigue decreased open skill-visuomotor performance in controls as well as badminton players.

4.1. Manipulation checks

The behavioral, subjective and physiological measures confirmed higher mental exertion in the Stroop task, indicating that a greater state of mental fatigue was successfully induced in MF compared to CON. Both subjective (higher perceived mental demand) and physiological (higher mean HR; Kohlisch and Schaefer (1996)) measures confirmed that the Stroop task was more mentally demanding than watching the documentary. Moreover, the decrease in accuracy in time, that is often found during the Stroop task, was also observed in the meaning stimuli in both the badminton players and controls (Marcora, Staiano, & Manning, 2009; Smith, Marcora, & Coutts, 2015). Performance on the Flanker task confirmed that cognitive capacity decreased in MF. Participants performed slower on the second Flanker task compared to the first. However, in CON, participants showed a similar deterioration in RT during the second Flanker task. This indicates that the induced mental fatigue did not affect Flanker performance in the present study, or, that a 90-min documentary might also have induced a certain degree of mental fatigue. Subjectively a higher feeling of mental fatigue was reported in MF compared to CON in both badminton players and controls.

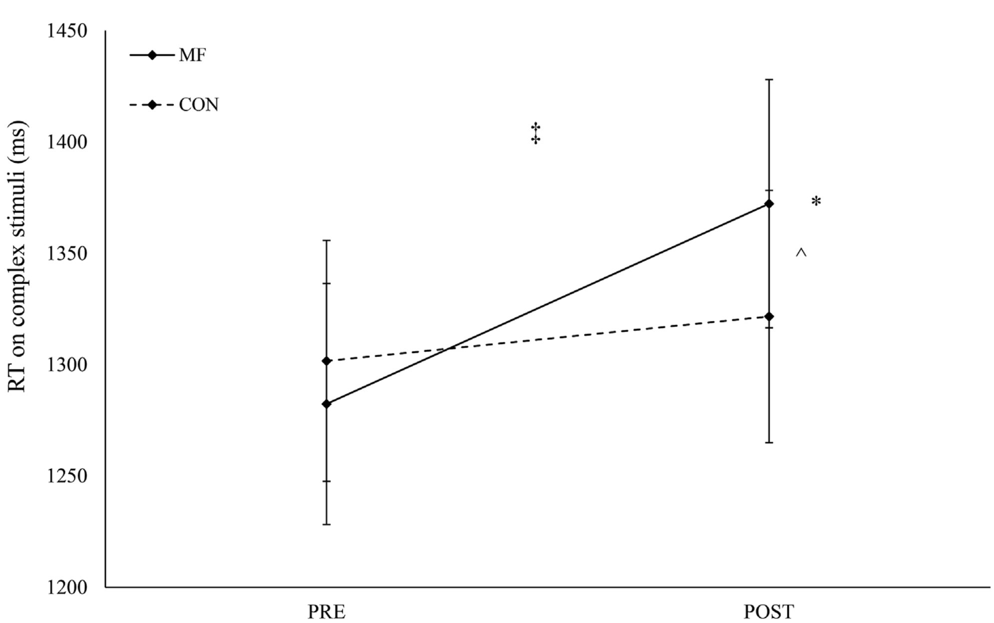

Fig. 5. Response time (RT) on the complex stimuli (independent of group; n = 20) during the visuomotor task (pre and post). ‡ denotes a significant condition × time interaction ($p < 0.05$). * denotes a significant main effect of time in MF ($p < 0.05$). ^ denotes a significant difference between MF and CON in the post visuomotor task. Data are presented as means ± SE.

4.2. Visuomotor task performance

On average, participants responded 7% slower on the complex stimuli (i.e. blue stimuli) compared to baseline in MF, while in CON no significant impairment was found. These results show that mental fatigue particularly impaired the RT to the complex stimuli, rather than the simpler stimuli (i.e. green, red and yellow stimuli), in both the badminton players and the controls. This is in accordance with previous studies on the effect of mental fatigue on cognitive performance (Fisk & Scerbo, 1987; van der Linden, Frese, & Meijman, 2003; van der Linden, Frese, & Sonnentag, 2003; van der Linden et al. (2003)), showing that executive control (i.e. the control to overrule an automatic response) is compromised by mental fatigue, but more automatic cognitive processing is relatively insensitive to this state.

According to the proposed models attempting to explain the link between mental fatigue and human performance (Kurzban, Duckworth, Kable, & Myers, 2013), similarities across the cognitive and the physical task should account for the observed mental fatigue-induced decrease in sport-specific psychomotor performance. In both the 90-min Stroop task and the 7-min visuomotor response task response inhibition was an important executive function determining task performance. In the Stroop task response inhibition was necessary for 100% of stimuli, while in the visuomotor task this function was employed for 25% of the stimuli. Both tasks also worked with a general response rule and an exceptional response rule, meaning that participants had to switch rules depending on specific color features of the stimuli. This task switching ability was necessary in 25% of the stimuli, as 25% of the stimuli presented in the Stroop task and in the visuomotor task contained the specific feature (i.e. in the Stroop when the letters of the word were colored in red; in the visuomotor task when the pad lighted op in the color blue) that indicated that participants had to switch to the exceptional rule in order to respond correctly. These two executive functions, response inhibition and task switching ability, represent two important similarities across the cognitive and the visuomotor task that might explain why carryover effects were observed.

In the present study mental fatigue did not affect Flanker performance or performance on the color stimuli in the Stroop task (i.e. both response inhibition-measures). As such, the effect of mental fatigue on response inhibition appears to be ambiguous. In contrast, task-switching ability was specifically assessed by accuracy and RT on the meaning stimuli in the Stroop task and RT on the blue stimuli in the visuomotor task. These measures specifically assessed task-switching ability due to their low appearance probability in comparison with the other stimuli in both tasks (i.e. the low appearance probability of both stimuli leads to a high relative rate of switch trials; Slama et al. (2017)), and performance on both these measures was impaired by mental fatigue. This reasoning puts forward task-switching as the main executive function that was deteriorated by mental fatigue and confirms the previously reported findings of a mental fatigue-induced impairment in task-switching ability (Lorist et al., 2000; Nakashima, Bouak, Lam, Smith, & Vartanian, 2018; Slama et al., 2017). Moreover the present findings add that this impairment also persists in a more sport-specific setting.

4.3. Badminton players vs controls

Badminton players only outperformed the controls on the visuomotor task. Performance on both the Stroop and Flanker task was similar between badminton players and controls. These findings lead to the conclusion that badminton players did not have a superior inhibitory control or task switching-ability compared to controls, rather badminton players demonstrated a superior visuomotor RT. This contrasts the observed superior inhibitory control in elite cyclists in the study of Martin et al. (2016), a finding that was suggested to play an important role in professional road cyclists being more mental fatigue resistant. In addition, unlike in the study of Martin et al. (2016), the badminton players in the present study did not demonstrate a greater resistance to mental fatigue than controls. Martin et al. (2016), and also other studies (Le Mansec et al., 2017; Smith et al., 2016; Veness et al., 2017), however already indicated that although superior inhibitory control might be a psychobiological characteristic of athletes that increases their resistance to mental fatigue, this does not mean they are immune to mental fatigue. It seems this statement is substantiated in the present study. Behavioral, subjective and physiological measures indicated that a greater state of mental fatigue was successfully induced in MF compared to CON in both badminton players and controls. The longer duration of mental load that was used in the present study (i.e. 90 min) compared to the studies of Martin et al. (2016) and Clark et al. (2019) (i.e. 30 min) might have induced more severe mental fatigue. This could explain why, in our study, mental fatigue impaired visuomotor performance not only in controls but also in badminton players. Another factor that could explain why we cannot substantiate the results of Martin et al. (2016) is the fact that the badminton players included in the present study were trained (see *participants characteristics*), but not elite. Therefore, caution is warranted in concluding that level of training does not improve the resistance to mental fatigue. A last factor that can be put forward to possibly account for the differing results between our study and the study of Martin et al. (2016) is the different type of athletic training that the athletes in both studies perform. Martin et al. (2016) suggested that aerobic training might have contributed to the superior inhibitory control of the professional road cyclists, while the badminton athletes in the present study will have focused more on non-endurance types of training, like for example technical skill training. Martin et al. (2016) emphasized that the aerobic training load of the professional road cyclists might be a factor that triggers brain adaptations (e.g. in the anterior cingulate cortex) that underlie superior inhibitory control. Further research is required to substantiate this hypothesis.

Thus, badminton players did not demonstrate superior inhibitory control or task switching-ability compared to controls. They did however demonstrate a superior visuomotor RT, hereby substantiating the statement of Hülsdünker, Strüder, and Mierau (2016) that open skill-athletes typically outperform non-athletes on visuomotor RT-tasks. The factors underlying this superior visuomotor RT in open skill-athletes compared to non-athletes can be multiple. Young, James, and Montgomery (2002) made an attempt to provide an overview of the main factors determining agility. This overview (Young et al., 2002) highlighted the important role of both physical (e.g. muscle strength and power) and cognitive (e.g. perceptual and decision making) components in visuomotor performance/agility. To explain the presence of this superior visuomotor performance in badminton athletes, Hülsdünker et al. (2016) specifically assessed the role of this cognitive component in further detail. They concluded that this superior visuomotor performance originates from faster visuomotor transformation in the premotor and supplementary motor cortical regions rather than from earlier perception of visual signals in the visual cortex (Hülsdünker et al., 2016).

4.4. Practical applications

The present study shows that mental fatigue impairs open skill-visuomotor performance in athletes and should thus be taken into account by trainers and coaches to optimize sport performance (e.g. avoid long tactical talks prior to competition). This stresses the need for future research to develop interventions that might be suitable to increase resistance to mental fatigue (e.g. brain endurance training; Marcora, Staiano, and Merlini (2015)) or combat the mental fatigue associated performance impairments (e.g. caffeine-maltodextrin mouth rinsing; Van Cutsem et al. (2017)). In addition the newly developed open skill-visuomotor task is shown to be a sensitive tool to assess the performance-impairing effect of mental fatigue. This provides a perhaps more suitable alternative to the traditional psychological cognitive tests (e.g.

Flanker task) for trainers and coaches who want to evaluate the individual mental fatigue-resistance of their athletes.

5. Conclusion

These findings provide evidence that badminton players have better visuomotor response time than controls. However, they do not seem to be more resistant to the negative effects of mental fatigue on open skill-visuomotor performance. Both badminton players and controls responded on average 7% slower on the complex stimuli in the visuomotor task compared to baseline in MF. Furthermore, this study suggests that cognitive tasks with a larger motor component, such as the visuomotor task, are more sensitive to the negative effects of mental fatigue than traditional cognitive tasks (e.g. Flanker task) that have a very small motor component.

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Conflicts of interest

No conflict of interest is declared by the authors.

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