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Ready, set, go: Cortical hemodynamics during self-controlled sprint starts

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ABSTRACT

Objectives: Successful sprint starts require self-control: Athletes need to avoid a false start (impulse control) and at the same time need to start as fast as possible (action initiation). Research from cognitive neuroscience shows that such self-control acts hinge on activity in areas in the lateral Prefrontal Cortex (lPFC). We are harnessing these findings in order to accurately analyze and better understand the neural basis of self-controlled sprint start performance.
Design: In a within-subject experimental design, participants executed three different sprint start sequences (Ready-Set-Go) for ten times each. In the *no-start* condition, participants only had to avoid producing a false start (impulse control) and in the experimental conditions - either with fixed or with supposedly variable set-start intervals - they additionally had to execute a fast start (impulse control + action initiation).
Methods: We used functional near-infrared spectroscopy (fNIRS) to assess cerebral oxygenation in the lPFC during sprint start in 33 male participants.
Results: Results show that cerebral oxygenation increased after the set-signal and this increase was particularly pronounced in the fixed and supposedly-variable start conditions. Post-hoc analyses further indicated that oxygenation differences between no-start and the two start conditions were particularly pronounced in anterior parts of the LPFC.
Discussion: This is the first study to reveal oxygenation changes in self-control relevant cortical areas during sprint start performance. This substantiates the claim that sprint starts impose self-control demands and provides a much called for application of neuroscience findings to the sport context.

1. Ready, set, go: cortical hemodynamics during self-controlled sprint starts

In many sports, performance depends in large parts on a good start (Brüggemann, Morlock, & Zatsiorsky, 1997; West, Owen, Cunningham, Cook, & Kilduff, 2011; Zanoletti, La Torre, Merati, Rampinini, & Impellizzeri, 2006). Depending on the race distance, starting performance accounted for up to 26% of the overall race performance in swimming competitions at the 2000 Olympic Games (Cossor & Mason, 2001). Sprint running is probably the most prototypical example to underline the importance of a good start. Indeed, the first 10m in sprint running are crucial for overall performance (e.g. Brown & Vescovi, 2012; Eriksen, Kristiansen, Langangen, & Wehus, 2009; Harland & Steele, 1997; Helmick, 2003; Salo & Bezodis, 2004; Slawinski et al., 2010).

In light of its importance, it is not surprising that a lot of research is aimed at improving sprint start performance. This research has focused on optimizing the start position (Eikenberry et al., 2008; Harland & Steele, 1997; Schot & Knutzen, 1992), the force rate (Harland & Steele, 1997; Helmick, 2003; Mero, 1988), and the reaction time and acceleration (Salo & Bezodis, 2004; Slawinski et al., 2010). Consequently, exercises to improve sprint start performance often focus on acceleration and speed improvement via conditioning and drill exercises (Sheppard & Young, 2006).

Beyond the physiological determinants of sprint start performance, recent research sheds light on the importance of cognitive components (Englert & Bertrams, 2014; Ille, Selin, Do, & Thon, 2013). The prototypical cognitive requirements for optimal sprint start performance are the capacity to control an impulse and to initiate a goal directed behavior: First, athletes need to control the impulse to start too early in order to avoid disqualification. Second, athletes need to respond as quickly as possible to the start signal in order to start swiftly into the race. Both processes rely on self-control (e.g., Brass & Haggard, 2007) as self-control refers to “the efforts people exert to stimulate desirable

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responses and inhibit undesirable responses" (de Ridder, Lensvelt-Mulders, Finkenauer, Marijn Stok, & Baumeister, p. 77). In sports psychology research, the strength model of self-control (Baumeister, Vohs, & Tice, 2007) has proven to be a useful framework to investigate self-control processes (Englert, 2016). According to the model, self-control is a limited resource that depletes when it is exerted (Baumeister et al., 2007). In this state of *ego depletion* individuals supposedly perform worse in tasks that rely on self-control. Research shows that high trait and state self-control are conducive to success in various life domains (Blain, Hollard, & Pessiglione, 2016) as well as in regard to sports performance (Englert, 2016; Englert & Wolff, 2015; Wagstaff, 2014). Of particular importance for the research presented here, Englert and Bertrams (2014) and Englert, Persaud, Oudejans and Bertrams (2015) showed that supposedly high state self-control was associated with better starting times and fewer false starts in sprint running. This underlines the importance of self-control for optimal response inhibition and efficient action initiation. Thus, sprint start performance requires the exertion of self-control and applying self-control coincides with improved performance. However, recent findings have questioned the empirical basis (e.g., Hagger et al., 2016; Wolff, Baumann, & Englert, 2018) and the mechanistic plausibility (e.g., Beedie & Lane, 2012) of the strength model. Therefore, the mechanisms that underly self-controlled sprint performance are still unclear. This knowledge gap is unsettling: Only a firm understanding of the involved mechanisms will enable coaches and researchers to design interventions to help athletes utilize their self-control to maximize sprint-start performance.

A large body of research has investigated the neuronal underpinning of self-control success and failure in other domains (Botvinick & Braver, 2015; Botvinick, Cohen, & Carter, 2004; Carter & van Veen, 2007; Shenhav et al., 2017). These studies point to the central role of the Prefrontal Cortex (PFC; its lateral parts [lPFC] in particular, Figure 1) - as a key structure in exerting self-control (e.g., Cohen & Lieberman, 2010; Miller & Cohen, 2001). The PFC has an ideal anatomical position to play a key role in self-control: The PFC receives inputs from most sensory systems and is strongly connected with motor system structures (that are relevant for voluntary behavioral control, Miller & Cohen, 2001). Within the PFC, different areas appear to be involved in distinct facets of self-control (e.g., Dubin, Maia, & Peterson, 2010; Miller & Cohen, 2001). For example, ventrolateral areas appear to be of particular importance for impulse control (Dubin et al., 2010).

Many of these studies used computerized cognitive tasks and some of these tasks pose self-control challenges that are similar to those induced by a sprint start (Di Russo, Taddei, Apnile, & Spinelli, 2006; Dixon & Christoff, 2012). For instance, in Go/No-Go tasks, participants need to respond to certain stimuli rapidly via a button-press (Go stimulus) unless a stop-signal is displayed (No-Go stimulus). Thus, reacting to Go-stimuli requires efficient action initiation (a button press), and the No-Go stimuli require inhibiting this response (e.g. Casey et al., 1997; Simmonds, Pekar, & Mostofsky, 2008). Typical measures recorded in this task are the number of commission errors (button presses although a No-Go stimulus was present), the number of omission errors (no button presses in response to a Go stimulus), and the time to respond to a Go stimulus (Go reaction time) (Simmonds et al., 2008). While it is unlikely that an athlete misses a start in a competitive setting (i.e., omission errors), false starts may be interpreted as commission errors and the relative efficiency of the start may be interpreted as the time to respond. It is therefore plausible that a sprint start and computerized self-control tasks such as a Go/No-Go task engage similar brain areas. We are not aware of any research that has investigated the cortical activation patterns during a sprint start, thereby leaving a research gap in the sport psychology literature. In addition, researchers have emphasized the need to test the broader applicability of findings from neuroscience, particularly in the fields of sports (Walsh, 2014).

A reason for this lack of translational research lies in methodological restrictions that are imposed by most neuroimaging techniques (Wolff, 2017). The necessity for measuring in a very constrained requirement (in the case of functional Magnetic Resonance Imaging) and a high vulnerability to motion artifacts (in the case for Electroencephalography, EEG) have historically limited the application for neuroimaging techniques in sports psychology research (Wolff, 2017). However, advances in artifact correction (especially in EEG research) and particularly the introduction of more portable and robust measurement techniques have facilitated the assessment of the 'sporting brain' (Walsh, 2014) in recent years. One such measurement technique is functional Near-Infrared Spectroscopy (fNIRS; for an introduction, see Ekkekakis, 2009). fNIRS is a non-invasive technique that uses NIR light to measure changes in oxygenated (HbO) and de-oxygenated (HbR) hemoglobin in the cerebral cortex (Scholkmann et al., 2014). While limited depth penetration prevents the measurement of deep brain areas, surface areas can be assessed reliably (Ferrari & Quaresima, 2012). Most importantly for the sports setting, fNIRS is comparatively robust to motion artifacts, has acceptable temporal resolution and due to its portability fNIRS can be used in settings with high external validity (Ekkekakis, 2009; Piper et al., 2014; Strangman, Culver, Thompson, & Boas, 2002; Wolff, 2017). For example, fNIRS has even been used to measure fluctuations in PFC activation when participants were fully exerting themselves in various endurance tasks (e.g., Rooks, Thom, McCully, & Dishman, 2010; Giboin, Gruber, Schüler, & Wolff, 2018; Wolff, Bieleke, Hirsch, Wienbruch, Gollwitzer, & Schüler, 2018). fNIRS has proven to be a reliable research tool for investigating group level effects (Scholkmann et al., 2014; Wolff et al., 2018). To further improve reliability of fNIRS instrumentation, researchers have for example focused on identifying emitter-detector separations that optimize signal-to-noise ratio (e.g. Germon et al., 1999), identifying wavelengths in the NIR spectrum with the best properties for measurement (e.g., Yamashita, Maki, & Koizumi, 2001) and the construction and evaluation of mechanisms to correct motion artifacts (e.g., Molavi & Dumont, 2012). The general properties of fNIRS along with these recent

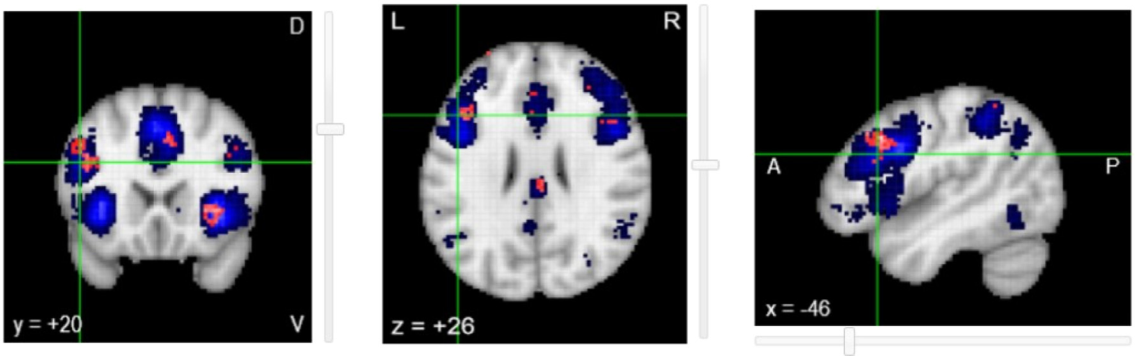

Figure 1. An automated synthesis on brain activations for the search term 'self-control' was conducted with neurosynth.org (http://neurosynth.org/). This instant meta-analysis of 428 fMRI studies shows that particularly areas in the lPFC are engaged in self-control.

advancements render fNIRS particularly useful for sport psychological research (Ekkekakis, 2009; Wolff, 2017).

1.1. The present study

In the present experiment, we used fNIRS to investigate lPFC activation during a sprint start. Specifically, we tested the hypothesis that the interval between the *Set* and the *Start* command in a sprint start is characterized by an increase in lPFC activation. Further, we investigated whether activation patterns differed as a function of three experimentally manipulated sprint-start sequences: Across three experimental blocks, all participants started after a predictable interval (*fixed* set-start interval condition), started after a supposedly unpredictable interval (*variable* set-start interval condition), or did not start at all (*no-start* condition). We tested the hypothesis that PFC activation would be higher in the experimental conditions (variable or fixed start) that imposed multiple self-control demands (impulse control and action initiation) than in the no-start condition where participants only had to avoid an accidental false start (impulse control). Moreover, we expected differences between the two experimental conditions, such that the condition where participants expected a variable set-start interval would produce a higher PFC activation than the fixed set-start interval. We expected that the expected unpredictability of the variable interval would increase cognitive control demands even further.

2. Methods

2.1. Participants and design

A priori power analysis with G*power (Faul, Erdfelder, Lang, & Buchner, 2007) revealed a minimum sample size of $N = 31$ to detect a medium effect ($f = 0.25$, $1 - \beta = 0.85$, $\alpha = 0.05$) in our within-subject design. To account for possible dropouts, we recruited a sample of $N = 33$ male students (age: $M = 22.9$, $SD = 2.9$). As this is the first study on the cerebral correlates of sprint starts, we recruited a homogenous sample thereby increasing statistical power at the expense of wider generalizability. Thus, we only included males aged between 18 and 30 years, who were involved in sports but not specifically in sprint running. Participants on average exercised 3.7 ($SD = 2.1$) times per week with an average duration of 78.9 ($SD = 18.7$ min) minutes per exercise bout and had about eleven years ($M = 10.9$, $SD = 6.1$ years) experience in their main sport. The study was conducted in accordance with the declaration of Helsinki and participants signed an informed consent form. When the experiment was completed (after about 90 min), participants were compensated (15€) and fully debriefed. All participants were given the option to withdraw their data, which none of the participants chose to do.

2.2. Measures

2.2.1. Standing sprint starts

Irrespective of the start condition, the same consecutive signals were presented (Figure 2). All signals were presented by a computerized voice, in order to present the same auditory information for each trial with the same inter stimulus interval and to avoid the possibility of experimenter bias. The signal "On your marks" instructed participants to place the supporting leg behind the starting line (red marker tape on the lab floor) and to stand with the other foot on a start mat (black rectangular mat on the lab floor). Six seconds later, the signal "Set" prompted participants to bend their knees and hip to shift their weight onto their front leg. To ensure a comparable and stable head position for each trial, participants were asked to fixate a red cross 1 m behind the start line. Seven seconds later, participants heard a start shot which was the "Start" signal. While no response was required in the no-start condition, in the fixed start and supposedly-variable start conditions participants were instructed to respond as quickly as possible and initiate their sprint movement. A second line (5 m behind the start line), was defined as the finish line after which participants were asked to abort the sprint. After each start signal, participants had a break of 30 s, in which they could slowly walk back to the starting line. This long break ensured that oxygenation changes could return to baseline level (Logothetis, 2003).

2.2.2. fNIRS measurement

A 8 Emitter + 8 Detector multichannel continuous-wave fNIRS imaging system (NIRSport, NIRx Medical Technologies LLC, NY, USA) was used to monitor changes in cerebral concentrations during the sprint starts. NIR light in two wavelengths (760 nm and 850 nm) was emitted at a sampling rate of 7.81 Hz. To capture fluctuations in LPFC activation, two 4 emitter + 4 detector arrays were bilaterally positioned over scalp sites corresponding to the lPFC (see Figure 3A and 3B). Optode placement was done according to the international 5/10 system (Oostenveld & Praamstra, 2001). Channels of interest were emitter-detector pairs with 30 mm separation. This resulted in nine channels on the left (channels 1–9) and in nine channels on the right (channels 10–18) hemisphere. The probes were fixated in a custom-made stretchy fabric NIRScap (EASYCAP GmbH, Herrsching, Germany). A retaining overcap (EASYCAP GmbH, Herrsching, Germany) was placed over the NIRScap in order to exert pressure evenly onto the probes, which enhances the contact between the probe tips and the scalp, stabilizes the setup against motion artifacts, and shields the optodes from ambient light.

2.2.3. Manipulation check

Motivation to do well in the sprint starts was assessed on a 7-point Likert-type scale (1 = not at all, 7 = very much): "How important was it to you to execute the sprint starts as fast as possible?" Additionally, participants were asked which sprint start condition was the most difficult for them (no-start, fixed-interval, supposedly-variable-interval) and if they found it difficult to avoid starting in the no start condition (yes/no).

2.3. Procedure

Participants were tested individually in the sport psychology lab.

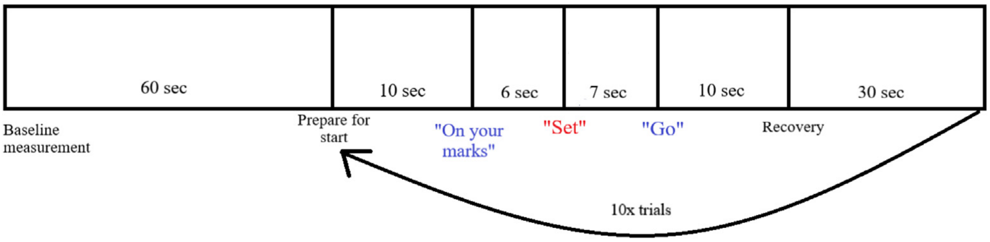

Figure 2. Illustration of a sprint-start sequence. The structure and timeframe are the same for all three sprint-start conditions. To prevent possible order effects, the order of start conditions was counterbalanced between participants. We deviated from a normal start for methodological reasons: The time interval between "Set" and "Go" is comparatively long. We decided to use such a long interval so we would be able to capture the hemodynamic response, which normally peaks within 7 s after a stimulus (Chiarelli et al., 2015). Further, starts were executed in standing position to avoid any strong head movements or frowns which could affect the quality of the fNIRS measurement. fNIRS data were collected continuously throughout the experiment. To maximize participant engagement and to document actual starting behavior, the sprint-starts were videotaped.

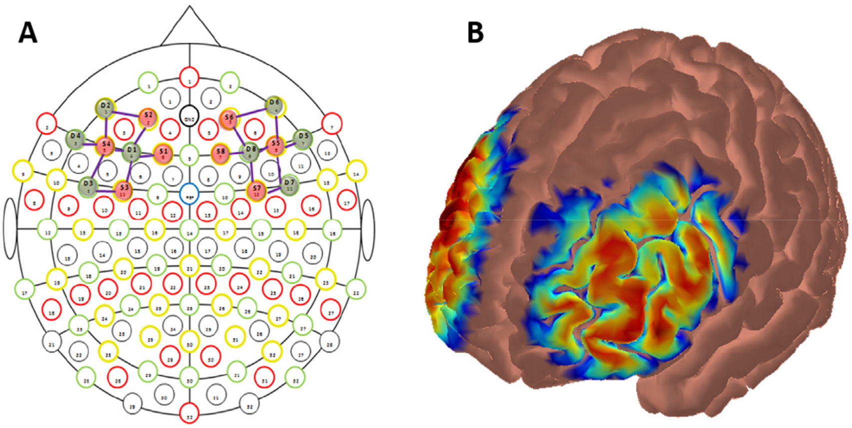

Figure 3. For the fNIRS measurement, emitters (E) and detectors (D) were positioned according to the international 5/10 system: E1 at F1, E2 at AF3, E3 at FC3, E4 at F5, D1 at F3, D2 at AF7, D3 at FC5, D4 at F7, E5 at F6, E6 at AF4, E7 at FC4, E8 at F2, D5 at F8, D6 at AF8, D7 FC6, and D8 at F4 (A.). The sensitivity profile (Atlas Viewer, Aasted et al., 2015) of the montage indicates that the chosen optode placements capture the LPFC reasonably well. It represents Monte Carlo random walks of $1e^7$ photons (per optode) migrating through a standard atlas (**B**).

Sessions lasted approximately 90 min. Upon arrival, participants were welcomed, signed a written informed consent, were surveyed for their compliance with inclusion criteria (i.e., no exercise and/or alcohol consumption the day before and no caffeine consumption up to 2 h prior to the experiment), and provided demographic data. Next, the experimenter installed the fNIRS equipment and optimized the fit until good signal quality was ensured. During the fNIRS installation, special care was taken to fix the setup in a way that head movements would not affect the signal too much (e.g., it was ensured that participants could freely move their head without pulling the optodes). The fNIRS imaging system was connected to a tablet computer and both were fixed on a base plate and stored in a light running backpack that was then worn by the subject. fNIRS recordings were transferred in real-time via Team Viewer® to an external computer to allow for a constant monitoring of signal quality. Prior to each block, the experimenter ensured that participants fully understood the sprint start procedure in the different conditions and were familiar with the standing sprint starts procedure. Participants completed 10 trials per start condition. After each block of ten trials, participants had a short break. After the final block, participants completed the manipulation check, were fully debriefed, payed, and thanked for their participation.

2.4. *Data analysis*

2.4.1. *fNIRS preprocessing*

HOMER2 (Huppert, Diamond, Franceschini, & Boas, 2009) was used to preprocess the raw fNIRS data. Firstly, channels with too high or too low optical intensity were removed. Then, optical intensity data were converted into optical density data by taking the logarithm of the signal. To correct for motion artifacts, a discrete wavelet transform was applied (IQR = 1; Molavi & Dumont, 2012). This method has been shown to be effective in correcting for motion artifacts and to allow for a better estimation of the true hemodynamic response (Brigadoi et al., 2014; Chiarelli, Maclin, Fabiani, & Gratton, 2015; Cooper et al., 2012). If further motion artifacts were present after the wavelet transform, then trials that were temporally close to the motion artifact (-2 to 10 s) were excluded from the analyses. Then, the corrected data were low pass filtered (0.5 Hz) and converted into HbO and HbR concentration changes using the modified Beer-Lambert law (Delpy et al., 1988). Following the recommendations by Essenpreis et al. (1993), differential path length factors were chosen differently for the two wavelengths (7.3 for 760 nm and 6.4 for 850 nm). Finally, we applied the hmBlockAvg function of HOMER2 to obtain corrected group averaged oxygenation values (Huppert et al., 2009).

2.4.2. *Channel selection*

As the experimental fNIRS configuration covers a large portion of the head, we did not expect uniform activation patterns across the head. To identify channels that should be included to the statistical analyses, we included those channels that—across all conditions and across all subjects—displayed a visually identifiable hemodynamic response to the “Set” stimulus (Yücel et al., 2015; Figure 4). Based on these data, we included four channels on the left hemisphere (S2-D2, S4-D2, S4-D4, S4-D3) and the corresponding four channels on the right hemisphere (S6-D6, S5-D6, S5-D5, S5-D7) into the statistical analyses.

2.4.3. *Statistical analyses*

We restructured and merged the data using R (RStudio Team, 2016). From the pre-processed block averages, two aggregate values were calculated per condition: Oxygenation in the 2 s prior to the set-signal and oxygenation in the timeframe five to 7 s after the set-signal. These intervals were chosen to obtain *baseline* oxygenation values and oxygenation values in response to the set-signal. The timeframe for analyzing the cortical response to the set-signal was chosen because the hemodynamic response function is expected to peak about 5 s after a signal (Huppert, Hoge, Diamond, Franceschini, & Boas, 2006) and since 7 s after the set-signal, the Start signal occurred. All statistical analyses were then performed with JASP (JASP Team, 2018). To test our hypotheses, we conducted a repeated-measures analysis of variance (ANOVA) with two within factors: To test whether lPFC oxygenation increased in response to the self-control demands imposed by an imminent sprint start, we compared baseline and response to set-signal as a within factor *Time*. To assess whether lPFC oxygenation differed as a function of the experimental condition, we compared the different sprint start settings as a three-level within factor *Condition*. Bonferroni corrected post-hoc tests were conducted to assess differences between factor levels.

3. Results

3.1. *Manipulation check*

Participants were generally motivated to perform a fast sprint start ($M = 5.88$, $SD = 1.24$, $Range = 3–7$). Most participants ($n = 16$) perceived the supposedly-variable start condition as the most difficult, followed by the fixed start condition ($n = 12$) and the no-start condition ($n = 5$). Still, 52% ($n = 17$) experienced the condition where no start was required to be somewhat difficult too.

3.2. *Main analyses*

Group averaged time courses of oxygenation changes from 2 s before the set-signal to 7 s after the set-signal show a constant increase in oxygenation for all conditions (Figure 5). This increase is more pronounced for the conditions were participants were asked to actually start the sprint on the start signal. This descriptive trend is corroborated by the results of the repeated measures ANOVA as indicated by significant main effects for time ($F(1,32) = 109.61, p < 0.001, \eta_p^2 = 0.77$)

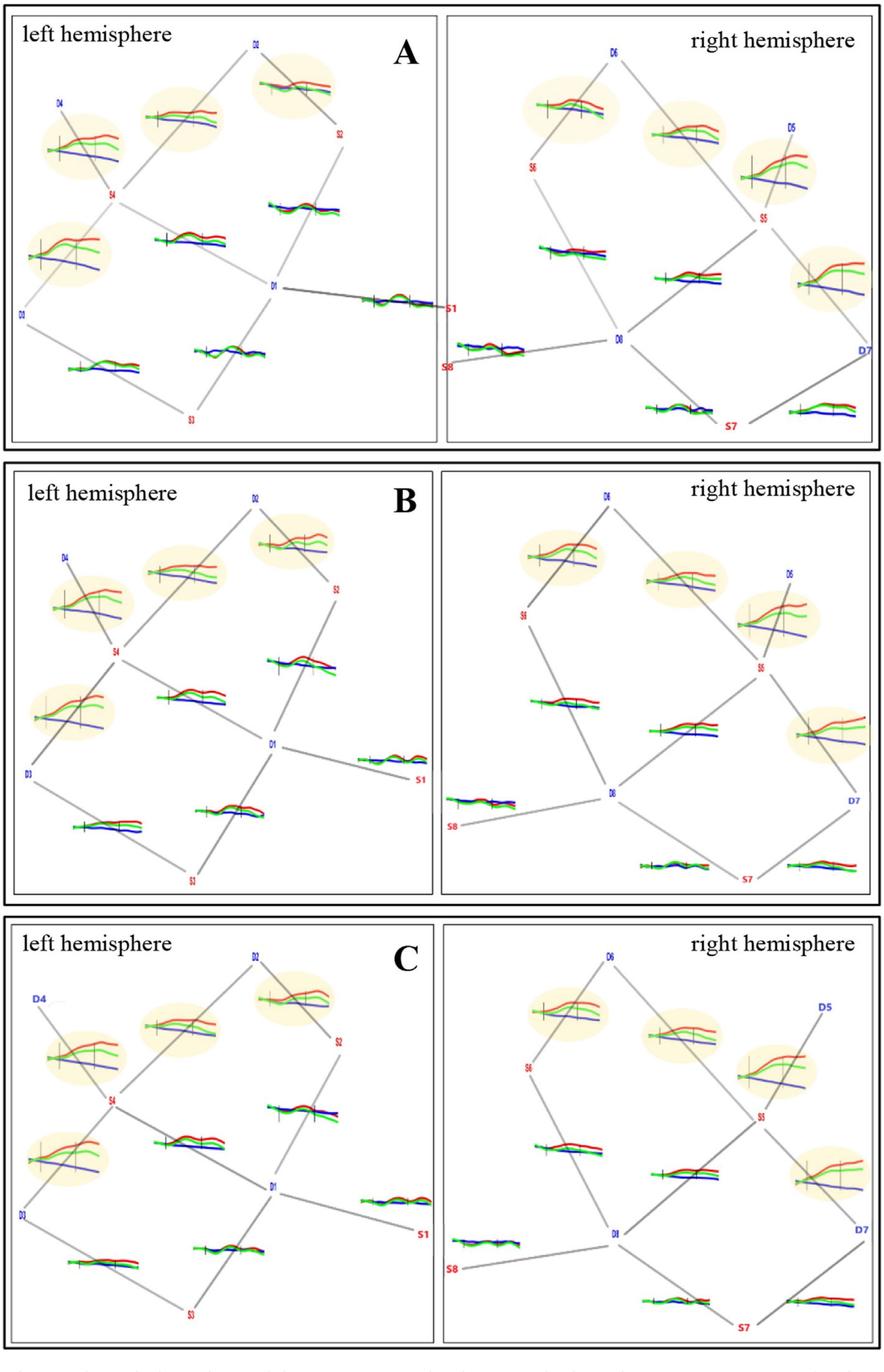

Figure 4. Selection of task-relevant channels from the used fNIRS montage. The three panels show the activation patterns for the no-start (**A**), the supposedly-variable start (**B**) and the fixed start (**C**) condition respectively. Channels that were included in the statistical analyses are highlighted (Yücel et al., 2015).

and condition, $F(2,64) = 12.34$, $p < 0.001$, $\eta_p^2 = 0.28$. This supports our hypothesis that lPFC oxygenation increases during the mental preparation of a sprint start.

Main effects are further qualified by a significant time × condition interaction, $F(2,64) = 12.51$, $p < 0.001$, $\eta_p^2 = 0.28$. Bonferroni corrected post-hoc tests indicate that oxygenation in the no-start condition is significantly lower compared to the fixed start ($p_{\text{bonf}} < .001$, $d = -0.66$) and the supposedly-variable start conditions, $p_{\text{bonf}} < .001$, $d = -0.66$. No significant difference was observed between the fixed start and the supposedly-variable start condition, $p_{\text{bonf}} < .99$. This supports our hypothesis, that the increase in lPFC oxygenation is higher when the experimental condition induces impulse control and action initiation simultaneously as opposed to when only impulse control is needed. Contrary to our hypothesis, whether the set-start interval was supposedly-variable or fixed did not differentially affect the observed oxygenation changes.

3.3. Post-hoc analyses

Exploratory visual inspection of the oxygenation changes in the analyzed channels indicated channel-dependent condition differences (Figure 4). Specifically, while a uniform increase in oxygenation appears to occur in ventral channels (S4-D3; S4-D4; S5-D5; S5-D7), the oxygenation increases in anterior channels (S2-D2; S4-D2; S5-D6; S6-

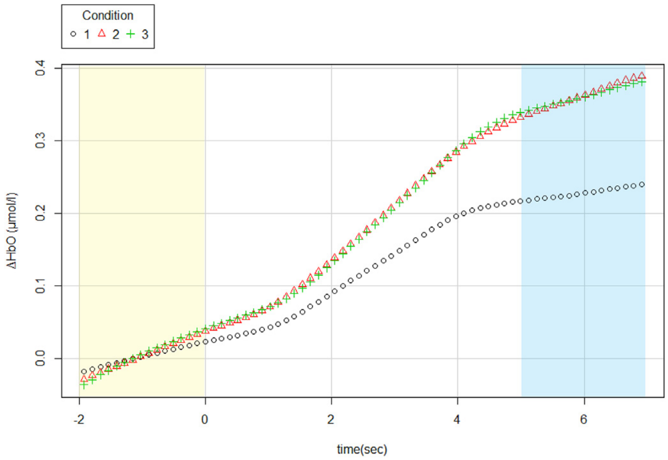

Figure 5. Visualization for the group and channel averaged time course for Hb0 changes from 2 s before the set-signal to 7 s after the set-signal for all analyzed channels. For statistical comparisons, we compared mean aggregated oxygenation at baseline (yellow shaded area) with oxygenation as a response to the set-signal (blue shaded area). The time course for oxygenation changes during no-start (condition 1), fixed set-start (condition 2), and supposedly-variable set-start (condition 3) conditions are represented by black circles, red triangles and green crosses.

D6) seems to be more pronounced in the conditions where participants had to perform an actual start. Consequently, the analyzed channels where further separated into anterior and ventral Regions of Interest (ROIs). Since the primary analyses revealed no differences between the fixed and supposedly-variable start condition, they were aggregated in the exploratory analyses. We then performed two paired samples t-tests – one on each ROI - to test if the differences between no start condition and the aggregated start conditions were of similar magnitude in both ROI's. In both ROI's the oxygenation change was significantly more pronounced in the start conditions compared to the no start condition, $ps < 0.01$. However, the effect size of this difference appeared to be higher in anterior parts ($d = 0.93$, CI95% = 0.51–1.33) than in ventral parts of the lPFC, $d = 0.54$, CI95% = 0.17–0.90. This indicates that activation in anterior parts was more specifically linked to the specific self-control demands that were induced by the start conditions.

4. Discussion

We investigated the cortical response to self-control demands imposed by a sprint start in a within-subjects fNIRS experiment. During a sprint start sequence (Ready – Set – Go), we found an oxygenation increase in the lateral Prefrontal Cortex (lPFC). lPFC activation increased during all sprint start sequences but this increase was more pronounced when participants executed the start and thus faced multiple self-control demands (impulse control + action initiation) as opposed to a singular self-control demand (impulse control). Exploratory post-hoc analyses indicated that activation changes occurred at different lPFC areas as a function of these specific self-control requirements. These findings are the first to provide neuroscientific support for the claim that sprint starts impose self-control demands and to shed light on the cortical processes that are involved in sprint starts. In addition, we provide a much called for application of findings from basic neuroscience to the sports context.

4.1. Sprint starts and self-control

Beyond this general support for the role self-control processes during sprint starts, our data provide insights into the specific mechanisms involved. Prefrontal oxygenation increased after participants heard the set-signal of a sprint start sequence, indicating that the immediate preparation for an upcoming start requires self-control. Specifically, cerebral oxygenation significantly increased in the last 2 s before the Start signal compared to the 2 s preceding the set-signal. From a self-control perspective, this finding makes sense: Sprinters have to be prepared to start their sprint as soon as they hear the Start signal. This situation poses conflicting self-control demands: To avoid a false start, sprinters have to control the impulse to start early; to start well, sprinters have to initiate the sprint as quickly as possible after the start-signal. Thus, good sprint starts require impulse control and action initiation. Research from cognitive neuroscience has repeatedly shown that the PFC plays a key role for self-control (Cohen & Lieberman, 2010; Miller & Cohen, 2001; Shenhav et al., 2017) and specifically for the regulation of motor behavior (Kujach et al., 2018; Miller & Cohen, 2001). The Expected Value of Control (EVC; Shenhav, Botvinick, & Cohen, 2013) framework offers a mechanistic explanation how control is determined and exerted. According to the EVC framework, the dorsal Anterior Cingulate Cortex (dACC) is involved in the decision on whether or not cognitive control should be exerted and that areas in the lPFC are then differentially involved in the actual implementation of this control command (Kujach et al., 2018; Shenhav et al., 2017). In the context of sprinting, if the participant is sufficiently motivated to aim for a good start, then the EVC is high and higher activations would be expected in areas that are relevant for executing the respective control command. Our findings fit well within this framework: Our participants were highly motivated to do well in the sprint starts and lPFC activation increased as the start approached. In addition, the differences between conditions also support this view. Both start conditions tapped into impulse control as well as action initiation self-control facets (to avoid early starts and enable quick starts after the signal), while the no-start control condition only tapped into the impulse control faced (to avoid starting). Both start conditions lead to a substantially higher increase in activation compared to the control condition, indicating that more extensive regulatory functions were engaged.

Contrary to our expectations, we did not observe any differences between the fixed and supposedly-variable set-start interval conditions. We expected a supposedly variable set-start interval to induce more uncertainty and therefore more self-control demands. However, as the manipulation check revealed, the number of participants who rated the fixed set-start condition as the most difficult was almost the same as for the supposedly-variable set-start condition. In addition, the official rules of the International Association of Athletics Federations (IAAF, 2015) do not define a fixed set-start interval in sprint starts. The expectation of a variable interval is therefore the norm rather than the exception in sprint running.

Interestingly, exploratory post-hoc analyses indicated that the magnitude of activation changes differed locally between the start conditions and the no-start condition. Although, overall activation was always higher for start conditions that imposed multiple self-control demands, this difference was more pronounced in anterior compared to ventral parts of the lPFC. Since, that the start conditions differed in regard to the specific self-control demands they imposed (i.e., impulse control only vs. impulse control + action initiation) this might indicate that action initiation in this task was regulated in more anterior parts and impulse control in more ventral parts of the lPFC. Indeed, the ventral part of the lPFC has been linked specifically with impulse control (Dubin et al., 2010). It is important to point out that these analyses were conducted post-hoc and that our study was not designed to differentiate the neural substrates of action initiation and impulse control. We therefore believe that investigating the specific contribution of action initiation and impulse control processes on sprint starts is a highly promising avenue for future research.

4.2. Contribution

Our findings build on and extend recent sport psychology research. The importance of self-control for sports performance is well established (e.g. Englert, 2016; Wagstaff, 2014) and being unwilling or unable to exert self-control is linked to reduced performance (e.g., Englert & Wolff, 2015). Englert and Bertrams (2014), for example, showed that sprint start performance depends on the capacity or willingness to exert self-control. When subjects had exerted self-control before a sprint start, they produced more false starts and had slower starting times as compared to subjects who had not exerted self-control.

Our study is an important contribution to the fields of sport psychology and cognitive neuroscience. For sport psychology, it provides first insights into the neural underpinning of self-control processes during sprint start. For future research, it will be interesting to investigate possible activation differences between elite sprinters and novices, and to assess the link between cortical response and actual sprint performance. As many sports require effective impulse control as well as action initiation, the relevance of these findings is not restricted to sprinting but extends to other sports. For example, in baseball inhibitory control is needed, in order to decide as fast as possible whether to swing or not (e.g., Kida, Oda, & Matsumura, 2005). For neuroscience, our research takes up recent calls to test theories from neuroscience in the more applied and externally valid field of sports (Walsh, 2014), thereby providing a more realistic test for findings that usually stem from very controlled and artificial experimental settings.

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