CAN EXERCISE BENEFIT EXECUTIVE FUNCTIONING FOLLOWING STRESS? A SCOPING REVIEW OF THE ROLE OF THE PREFRONTAL CORTEX

by

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ABSTRACT

Daily stress is pervasive for many Canadians. It can lead to unpleasant feelings and is associated with changes for the concentration of cortisol and cerebral blood flow. Aerobic exercise presents a readily accessible adjunct with, or an alternative to, current interventions to manage stress. The prefrontal cortex (PFC) of the brain is affected by aerobic exercise, stress as well as in our ability to perform a variety of tasks that involve executive functioning. The purpose of this study was to conduct a scoping review of the literature to summarize evidence on the involvements of aerobic exercise on stressor-induced changes on executive functioning, as well as the involvement of the PFC. Potential studies were searched on PubMed and PsycInfo, and ten studies were included in the research synthesis. Results suggest the involvement of the PFC, such as the dorsolateral PFC during inhibition and working memory following stress or aerobic exercise, as well as the utility of functional neuroimaging to investigate these topics of the literature.

LIST OF ABBREVIATIONS USED

BOLD	Blood oxygen level dependent
EEG	Electroencephalography
fMRI	Functional magnetic resonance imaging
fNIRS	Functional near-infrared spectroscopy
HPA	Hypothalamic-pituitary-adrenal
MEG	Magnetoencephalography
MIST	Montreal Imaging Stress Task
PET	Positron emission tomography
PFC	Prefrontal cortex
TSST	Trier Social Stress Test

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1. Introduction

1.1 Prevalence of Stress and the Role of Aerobic Exercise

Between 2018 and 2019, about 2 million Canadians between 18 and 34 years of age have reported moderate to high levels of daily stress (Statistics Canada, 2019). In Nova Scotia, around 30, 000 adults between 18 and 34 years of age reported moderate to high levels of daily stress on the same time period (Statistics Canada, 2019). Stressful experiences change over the life course, such as meeting work deadlines, writing a difficult email, preparing a presentation or completing a dissertation during a global pandemic. These experiences, as well as other forms of stress, lead to feelings of anxiety (Rimmele et al., 2009) and restlessness (Klaperski et al., 2013; Rimmele et al., 2007). Because stressful experiences can be debilitating, the literature has proposed ways for individuals, to manage stress (Diamond, 2015). More precisely, individuals have been suggested to engage in activities that facilitate feelings of positivity, self-efficacy, and social support (for a discussion see Diamond, 2015). Activities that foster these feelings may alleviate the deleterious effects of stress on the individual, by targeting the same bodily systems that are affected through stress and, at the same time, necessary to perform various tasks (Diamond, 2015). Some of these activities are subserved within the general category of aerobic exercise. Engaging in daily walks with a loved one can, for instance, foster feelings of positivity, and support. Here, of importance is the view that participating in aerobic exercise is associated with increased blood flow to areas of the brain that, in turn, provides one source of energy to perform various tasks following acute stress.

1.2 Stress Effects on HPA Axis Function and PFC Function

In order to understand, how aerobic exercise may help manage stress, it is first important to acknowledge, how the body responds to stress. At a broader level, the body responds to stress

in the services for restoring energy (Dedovic et al., 2009; Herman et al., 2003). A stressful event is a multistage process, that is characterized with the perception of, and the response to, an event that poses a potential threat for the individual (Dedovic et al., 2009). As Figure 1 has shown, the perception of a stressor results in the production of the corticotropin releasing hormone from the hypothalamus. Once released, corticotropin releasing hormone reaches the pituitary gland which stimulates the release for adrenocorticotropic hormone. Following secretion, adrenocorticotropic hormone reaches the adrenal gland, which stimulates cortisol production. This cascade of events represent the body's gradual response to real or perceived threat, the end-product of which is the secretion of cortisol from the hypothalamic-pituitary-adrenal (HPA) axis. At a broader level, the HPA axis response to stress is associated with brain activity which as discussed below, involves regions of the prefrontal cortex (PFC; Dedovic et al., 2009; McEwen, 2007).

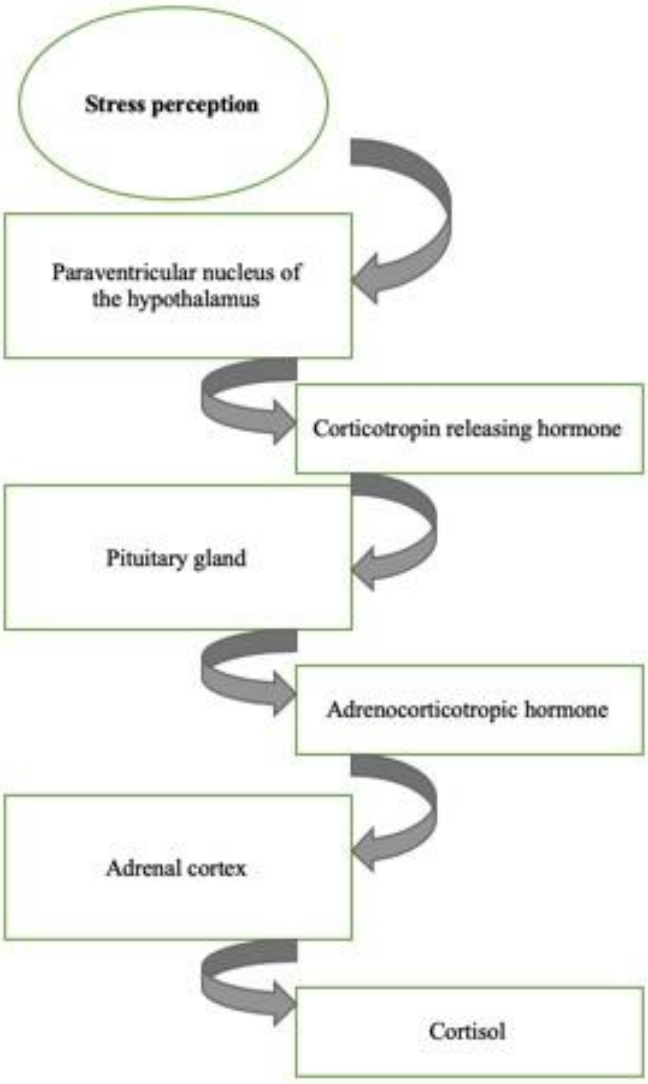

Figure 1. **HPA axis response to the perception of stress**. The figure shows the HPA stress response, as described by Dedovic et al. (2009). Here, a cascade of events gradually follow stress perception, in which an activation of the paraventricular nucleus of the hypothalamus leads to the eventual release of the glucocorticoid hormone, cortisol, from the adrenal cortex.

Because stress has been defined in a variable manner within the literature (for an example see Dickerson & Kemeny, 2004; Mason, 1968; McEwen, 2000), the present review defines stress as a *social interaction*, in which the individual perceives that his or her performance is negatively

evaluated by others, but cannot physically leave the situation. This definition of stress mirrors the concept of psychosocial stress by the literature. As such, this review uses *stress* and *psychosocial stress* interchangeably but, in each case, uses the term in reference to the definition above, unless stated otherwise.

In the past, regions of the PFC have been proposed to respond to different forms of stress, in concert with the HPA axis. As the top panel of Figure 2 suggests, the lateral, medial as well as the ventral regions of the PFC typically show an inverse relationship with the HPA axis response to stress. When variations for the Montreal Imaging Stress Task (MIST; Dedovic et al., 2005), as well as when modifications of the Trier Social Stress Test (TSST; Kirschbaum et al., 1993), have been selected to induce an acute state of psychosocial stress, the anterior cingulate cortex, frontal gyrus, orbitofrontal cortex, as well as the dorsolateral, dorsomedial and ventromedial PFC reveal changes in the concentration of cerebral blood flow associated with changes in the concentration of salivary cortisol (Dedovic et al., 2009; Eisenberger et al., 2007; Kern et al., 2008; Pruessner et al., 2008; Wang et al., 2005; Wheelock et al., 2016). The relationship between alterations in PFC blood flow that occur in parallel with alterations in cortisol concentration, demonstrates the well-known, fight-or-flight response to stress. As the body mobilizes energy for an individual to fight or flight under stress, a cascade of events take place in the brain that are associated with changes in the concentration of cortisol in saliva (Dedovic et al., 2009; McEwen, 2007).

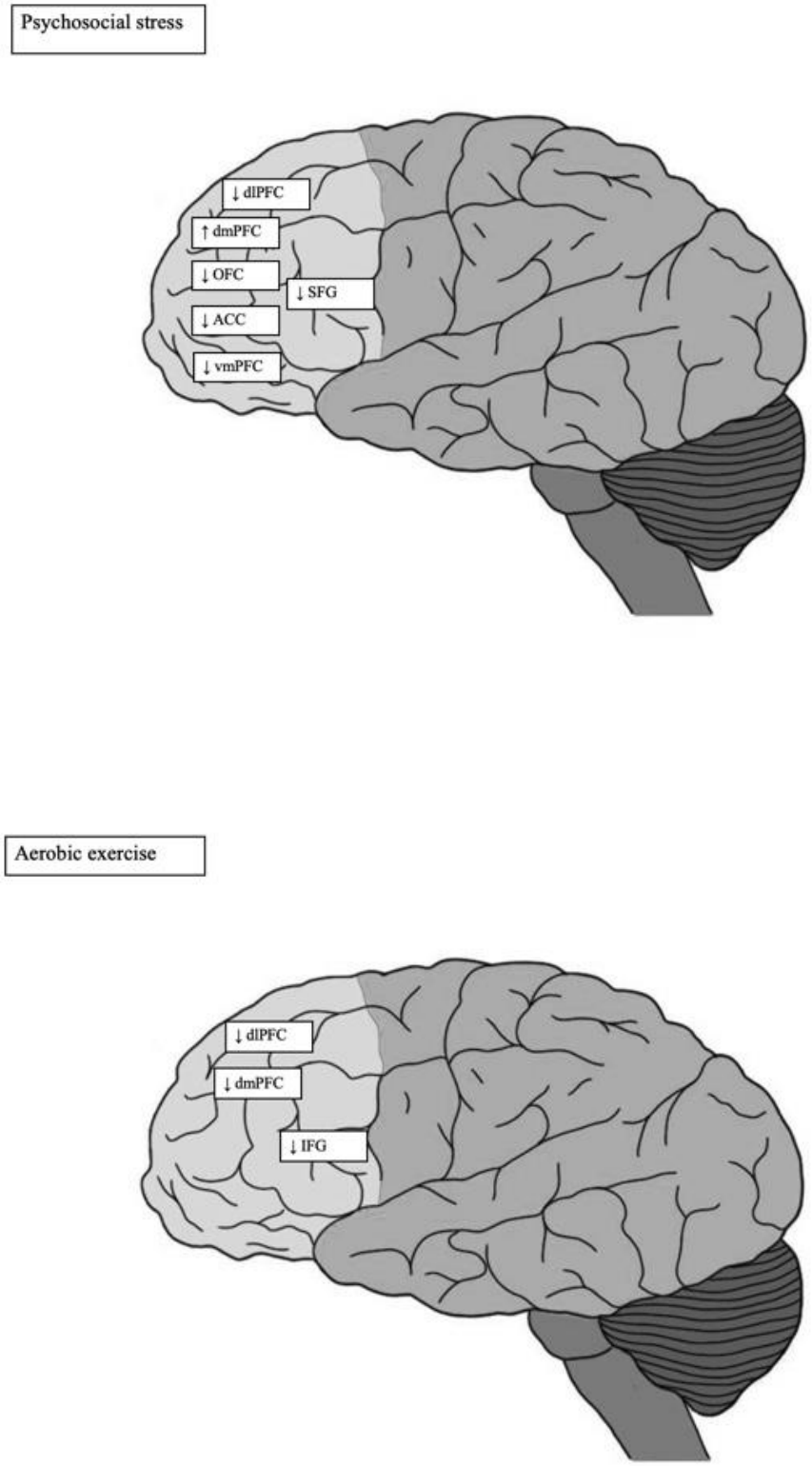

Figure 2. **PFC and HPA axis responses to psychosocial stress and aerobic exercise**.

Note. dlPFC represents dorsolateral PFC; dmPFC represents dorsomedial PFC; OFC represents the orbitofrontal cortex; SFG represents the superior, frontal gyrus; ACC represents the anterior cingulate cortices; vmPFC represents the ventromedial PFC; IFG refers to inferior frontal gyrus. This figure represents the relationships between activation in areas of the PFC and activation of the HPA axis as reported by PET (Kern et al., 2008; Pruessner et al., 2008) and fMRI (Dedovic et al., 2009; Eisenberger et al., 2007; Wang et al., 2005; Wheelock et al., 2016; Zschucke et al., 2015) during acute manipulations of psychosocial stress or aerobic exercise. ↑ represents that a positive relationship was reported whereas ↓ represents a negative relationship was reported by the above literature (Dedovic et al., 2009; Eisenberger et al., 2007; Kern et al., 2008; Pruessner et al., 2008; Wang et al., 2005; Wheelock et al., 2016; Zschuke et al., 2015). Note that both top and bottom panels are based on findings from the broader literature.

As Herman et al. (2003) have explained, the secretion of cortisol from the HPA system is intended to allow the individual, to survive potential threat to his or her body. While under stress, the brain is involved in our ability to regulate emotion as well as in our abilities to process, select and execute our responses to stress (Dedovic et al., 2009; Pruessner et al., 2008). As Pruessner et al. (2008) have explained, the anterior cingulate cortex is involved in our appraisals of stress and in action selection. When stress results in unpleasant feelings, the superior frontal gyrus (Kern et al., 2008) and the ventromedial PFC (Wang et al., 2005) are implicated in emotion regulation. In cases when overcoming stress implicates problem solving, the dorsolateral (Dedovic et al., 2009; Pruessner et al., 2008; Rosenbaum et al., 2018) and dorsomedial (Dedovic et al., 2009) PFC may be involved in addition to the anterior cingulate cortex, superior frontal gyrus, ventromedial PFC as well as other brain regions. As the above literature suggests, several brain regions are thought to be necessary to the stress response, and these regions are localized in the PFC. Of course, it is

important to acknowledge that brain regions, other than those described above, are necessary for the stress response, such as the amygdala, which is involved in the appraisal of stress (Pruessner et al., 2008; Taylor et al., 2008b). These findings are illustrated in the top panel of Figure 2.

1.3 Protocols to Induce Psychosocial Stress

In the previous section the TSST (Kirschbaum et al., 1993) and the MIST (Dedovic et al., 2005) were referred to, with respect to how psychosocial stress has been manipulated within past literature to evaluate the influences of stress on HPA axis function and PFC function (Dedovic et al., 2009; Eisenberger et al., 2007; Kern et al., 2008; Pruessner et al., 2008). Each procedure may be used to induce an acute state of psychosocial stress for participants because each encompasses a social interaction where the participant performs one or more tasks, his or her task performance is negatively evaluated by others, and task demands are unpredictable to the participant (Dedovic et al., 2005; Kirschbaum et al., 1993).

For the traditional version of the TSST (Kirschbaum et al., 1993), the participant prepares a speech that he or she must make in front of a committee. Unknown to the participant, his or her speech is followed, by a serial subtraction task, in which the participant is instructed to subtract a 2-digit number from a 4-digit number backwards. Following every error, the participant is told to restart the serial subtraction test from one of the committee numbers. From speech preparation to the cessation of serial subtraction, the TSST is less than 30 min (Kirschbaum et al., 1993), and is associated with increased concentration of salivary cortisol (Dickerson & Kemeny, 2004). MIST, in comparison, incorporates components of TSST (Kirschbaum et al., 1993) and the Trier Mental Challenge Test (Kirschbaum et al., 1991). Here, the participant performs arithmetic problems for addition, subtraction, multiplication, as well as division, that necessitate one or multiple order of operations (Dedovic et al., 2005). To produce a state of negative social evaluation the participant

is constantly told by one or more research investigators that his or her performance is inadequate (Dedovic et al., 2005). While each protocol has been modified since its conception, the principal characteristics to induce psychosocial stress for each remains the same, in that a participant feels inadequate from figures of authority in a situation that emphasizes optimal performance.

1.4 Exercise Effects on HPA Axis Function and PFC Function

As the above literature suggests acute experiences with psychosocial stress are associated with concentration changes in salivary cortisol and cerebral blood flow (for a review see Dedovic et al., 2009). With thoughtful study design, one line of research complements the evidence above by showing that the acute influence of MIST (Dedovic et al., 2005) on HPA and PFC functioning may be modulated by aerobic exercise (Zschucke et al., 2015). More precisely, Zschucke and co-workers observed that men who participated in 30 min of walking or running at 60-70% maximal oxygen reuptake showed a reduced cerebral blood flow concentration in the inferior frontal gyrus of the ventrolateral PFC as well as in the dorsolateral and dorsomedial PFC, following the end of exercise, in comparison to men who participated in 30 min of light stretches. Within this study, it was also reported that the exercise-induced reduction in PFC cerebral blood flow, was associated with no changes in salivary cortisol responses following exercise as well as reductions in salivary cortisol responses during the MIST (Zschucke et al., 2015). Together, the results provide support for the general involvement of the PFC during acute aerobic exercise and stress in young healthy men (Zschucke et al., 2015). Yet, executive functioning was not investigated, which is important to evaluate in this context, as evidence supports the general involvement of the PFC during tasks that require executive functioning (Diamond, 2013).

1.5 Assessments of Executive Functioning

Executive functioning refers to a set of cognitive processes, which are thought to underlie much of our behaviour (Diamond, 2013; Guiney & Machado, 2013). Although many of these are interrelated in the service of our ability to perform various day-to-day tasks (see *Section 1.7*), the concept of flexibility, inhibition, and working memory has each been thought to be a core aspect of executive functioning (for a discussion, see Diamond, 2013). To that end, different tasks have been developed to assess these core executive functions within a laboratory setting.

For instance, flexibility is commonly assessed using variations of task switching. Here, a participant is required to perform a test by applying one of multiple task rules, and the participant must learn when to "*switch*" how he or she performs the task, based on limited feedback (see Bae & Masaki, 2019; Kalia et al., 2018b, for examples). While various assessments have been used to assess flexibility in this manner (for a discussion, see Diamond, 2013), many of the experimental tasks used are a variation of the Wisconsin Card Sorting Task (Heaton, 1993). Here, a participant sorts a series of cards according to colour, number, or shape. Yet, only one sorting criterion stays correct with each trial, and the participant must learn, through restricted or no feedback, from the experimenter, when a previous sorting criterion is no longer correct, and to employ an alternative sorting criterion, to perform the task correctly (Heaton, 1993; Kalia et al., 2018b).

With inhibition, variations of a Go/NoGo (Dierolf et al., 2017, 2018; Jiang & Rau, 2017), a stop-signal (Chang et al., 2020b) task, or a Stroop (Stroop, 1935) task has been used in order to test this core executive function. As Diamond (2013) explained these tasks overlap, yet differ, in the components of inhibition investigated. These tests assess inhibition, in that a participant must select which pieces of information to attend to within each trial, and based on what he or she was instructed, to prevent oneself, from making a response. Variations for Go/NoGo, stop-signal, and Stroop tasks differ in the stimulus features, to which a participant must attend, as well as whether

correct performance requires inhibiting a response and doing nothing (Go/NoGo), or inhibiting a response and applying a different response (Stroop). In modifications of a Go/NoGo paradigm, a participant applies a keypress or verbal response when he or she sees a specific stimulus, such as a face presented in a red frame (Jiang & Rau, 2017). Yet in a minority of trials, another stimulus appears, such as a face presented in a blue frame (Jiang & Rau, 2017), which indicates that he or she must not respond at all. With a stop-signal task, the participant often sees a specific stimulus that indicates a keypress or verbal response should be made. Yet, during a minority of trials, this stimulus is immediately followed by another stimulus which indicates that the response, which a participant has likely initiated, should not be made. Here, a response must be inhibited when one is assumed to have already initiated a somewhat automated response in contrast to the Go/NoGo task, in which inhibiting a response is assumed at the start of the trial, when such a response has been unlikely initiated (Diamond, 2013).

In comparison, variations of the Stroop task (Stroop, 1935) generally require participants to inhibit an automated response in favour of making a less automated response. Here, trials that do not require inhibition present participants with a colour-word in each trial, such as "red", and participants make a keypress or verbal response corresponding to its word meaning or to the ink colour in which the word was presented (Diamond, 2013; Stroop, 1935). Here, the word appears in black ink ("red" printed in black) or in a compatible ink colour ("red" printed in red). In these trials, inhibition is not required, because a participant only reads the word presented, which is an automated response, requiring little to no effort. For other trials, a word appears in an ink colour that is incompatible with the word itself ("red" printed in blue) and the participant is told that he or she must respond to the ink colour in which the word was displayed. Here, a participant must inhibit the automatic tendency to read the word (Diamond, 2013), and must instead ignore what

the word suggests and respond to its ink colour, a less automatic response (Diamond, 2013). As such, variations of a Stroop task assess our ability to attend to different stimulus features, which vary across trials and, on some trials, to inhibit an automatic, though inappropriate, response, in favour of a less automatic, yet appropriate, response in the service of accurate task performance (Diamond, 2013; Stroop, 1935).

Finally, working memory has been commonly assessed through variations of the *n*-back paradigm (Li et al., 2014, 2019; Luettgau et al., 2018; Qin et al., 2009; Van Ast et al., 2016), or through variations of the Sternberg Item Recognition task (Sternberg, 1969). Here, a participant must maintain information and recognize whether the current information presented includes the to-be-remembered item content. In a common *n*-back task, the participant makes a keypress or verbal response to indicate whether the currently presented letter or number was presented, from a pre-determined number of trials ago. In cases when a participant must recognize whether or not the current display appeared from three trials previously (3-back), information may be more difficult to recognize, in comparison to when he or she must recognize whether or not the current display appeared during the preceding trial (1-back). As such, modifications of the *n*-back test assess features of working memory, in which a participant must maintain a single piece of information, for a few seconds to a few minutes (for examples, see Li et al., 2014, 2019; Luettgau et al., 2018; Qin et al., 2009). Yet, the concept of working memory is not limited to our ability to maintain and recognize information (Diamond, 2013).

In addition to the capacity to maintain and recognize information, working memory has been assessed with variations of the Sternberg Item Recognition task (Sternberg, 1969). Here, a participant must maintain information from a previous display, which may require him or her to maintain upto 16 items in mind, and recognize whether the to-be-recognized content, which can

potentially involve multiple information content, were shown in the current display. Because of this, modifications for the item recognition task (Sternberg, 1969) assess our ability to maintain, search for, as well as update information held in mind. By comparison, modified versions of the *n*-back task are designed to assess our ability to maintain as well as update information, without the need to search through an array of information in a goal-directed manner. Identical with that of flexibility, and inhibition, the concept of working memory can be decomposed into particular cognitive processes, and the assessment used is designed to isolate one or more of the processes while minimizing the influence of other cognitive processes, which may not be of interest to the experimenter (Diamond, 2013).

1.6 Neuroimaging Instrumentation

The PFC is involved with tasks that require executive functioning, and the activity in the PFC may be modulated from stress (for a review, see Alvarez & Emory, 2006; Diamond, 2013). More precisely, evidence suggests that stress-induced changes in cerebral blood flow for regions of the PFC are associated with alteration with cognitive flexibility (Kalia et al., 2018b), response inhibition (Chang et al., 2020b), and working memory (Van Ast et al., 2016). Furthermore, it has been suggested that exercise-induced changes in cerebral blood flow in the PFC are associated to improvements with inhibition (Yanagisawa et al., 2010) whereas electroencephalographic (EEG) activity within the PFC, is associated with cognitive flexibility (Bae & Masaki, 2019), as well as working memory (Hwang et al., 2019). In order to understand the evidence above, however, it is first important to understand how PFC function is assessed, and how these instruments predicate on the activity of neurons.

As Müller-Putz and co-workers have illustrated, our brain processes information, through nerve cells called neurons (Müller-Putz et al., 2014). Because observing human neurons function

directly *in vivo* is challenging, over the years, numerous instruments have been developed for the indirect examination of brain functioning. Some of these instruments include functional magnetic resonance imaging (fMRI), functional near-infrared spectroscopy (fNIRS), single-cell recordings as well as magnetoencephalography (MEG) and EEG.

Single-cell recording records electrical activation from a single neuron (Heinricher, 2014; Ludvig et al., 2001; Marblestone et al., 2014; Ratcliff et al., 2007) whereas EEG and MEG attain changes in the electrical activation, and changes in the magnetic field, associated with changes in neuronal activation, respectively (Baillet, 2017; Braeutigam, 2013; Hari & Salmelin, 2012; Lotte et al., 2015; Müller-Putz et al., 2014; Sato et al., 1991; Singh, 2014). In fMRI, fNIRS and PET, a researcher obtains information about brain function through changes in the properties of regional cerebral blood flow, that follow changes in neuronal activation (Bunce et al., 2006). Specifically, PET records changes in the concentration of glucose metabolism by cerebral blood flow (Decety et al., 1994; Phelps, 2000; Van Den Hoff, 2005; Ziegler, 2005) whereas fMRI records changes to the concentrations of deoxygenated hemoglobin in cerebral blood flow, in the form of the blood-oxygenation-level-dependent (BOLD) contrast (Glover, 2011), associated with changes in neural activity. As well, fNIRS obtains changes for the concentration of oxygenated hemoglobin as well as deoxygenated hemoglobin in cerebral blood flow, in the form of changes for the absorption of near-infrared light in the 650-1, 000 nm range associated with changes in neuronal activity (for a review, refer to: Bunce et al., 2006; Davies et al., 2017; Dieler et al., 2012; Ferrari, & Quaresima 2012; Murkin & Arango, 2009; Quaresima et al., 2012; Torricelli et al., 2014). In such respect, a researcher can evaluate the involvement of the PFC during various tasks, through different types of instrumentation. Finally, diffusion tensor imaging is not used to assess PFC function, because

it visualizes water diffusion (Alexander et al., 2007; Basser et al., 1994, 2000). As such, it is not ideal to examine PFC function and is more appropriate to characterize PFC structure.

1.7 Stress- and Exercise-Induced Changes in Executive Functioning

In the past literature, one area of interest concerns the modulatory role of aerobic exercise on stress-induced changes on executive functioning and the involvement of the PFC during these situations. Executive functioning refers to a class of processes, that are thought to be necessary to our ability to perform various tasks, such as processing information, selective attention as well as action selection (Diamond, 2013; Guiney & Machado, 2013). Of interest are the sub-components of flexibility, inhibition and working memory. These processes often underlie various day-to-day tasks like the day-to-day act of going grocery shopping, in which the ability to choose a different product, when the desired product is unavailable, predicates on flexible thought and the ability to resist buying unnecessary products predicate on inhibition and working memory. Flexibility may consequently be defined as the capacity to adapt to change (Diamond, 2013; Guiney & Machado, 2013). By comparison inhibition usually refers to inhibiting a response in a goal-directed manner while working memory commonly refers to the temporary maintenance, manipulation, as well as the updating, when necessary, of information (Diamond, 2013).

As mentioned above, aerobic exercise may modulate the influences of stress on executive functioning. For instance, various types of aerobic exercise are associated with a reduced cortisol responsivity to the TSST (for an example see Klaperski et al., 2013; Rimmele et al., 2005, 2007), and evidence from fMRI (Li et al., 2019) and fNIRS (Dupuy et al., 2015) studies posit how acute as well as chronic aerobic exercise may be associated with concentration changes in oxygenation in regions of the PFC during assessments of inhibition (Dupuy et al., 2015) and working memory (Li et al., 2019). Specifically Klaperski et al. (2013) found a lower salivary cortisol response to a

group version of the TSST (von Dawans et al., 2012) in women who reported participating in > 2 h of physical activity each week, in comparison to the cortisol responses observed in women who reported engaging in < 2 h of physical activity each week. Similarly, Rimmele et al. (2007, 2009) reported that males who reported participating in > 2 h of physical activity each week exhibited a lower salivary cortisol response to the TSST in comparison to men who reported engaging in < 2 h of physical activity per week. In a potentially related finding, Dupuy et al. (2015) observed that physically active women, defined as those who achieved a mean maximal oxygen reuptake value of 46.6 ± 7.0 ml/kg/min, during a graded maximal exercise test, showed a greater increase for the concentration of oxygenated hemoglobin within the right inferior frontal gyrus during a modified Stroop task in comparison to the findings observed for comparatively physically inactive women, defined as those who achieved a mean maximum oxygen reuptake value of 36.4 ± 5.3 ml/kg/min during the graded maximal exercise test. Owing to the role of physical activity level in executive functioning, Li et al. (2019) found that physically active women defined as those that achieved a mean maximum oxygen reuptake value of 26.50 ± 1.89 ml/kg/min, during a graded exercise test, revealed a greater BOLD contrast in the left anterior cingulate cortex during 2-back following 20 min of cycling at 60-69% heart rate reserve in comparison to that observed among comparatively physically less active women, defined as those who achieved a mean maximum oxygen reuptake value of 19.86 ± 1.00 ml/kg/min during the graded maximal exercise test.

1.8 Potential Involvement of Aerobic Exercise on Executive Functioning During Stress

As the above literature suggests, various forms of aerobic exercise can be associated with increased prefrontal oxygenation in individuals who perform inhibition tests (Dupuy et al., 2015) or working memory tests (Li et al., 2019) in comparison to when these tests are performed under control conditions. By comparison, fMRI research has shown that an acute psychosocial stressor,

in the form of a modified TSST (Kirschbaum et al., 1993), may be associated with a reduction in prefrontal oxygenation in participants who perform working memory tasks following the stressor manipulation in comparison to participants who perform the same tests following a non-stressful control condition (Luettgau et al., 2018). Together, these findings indicate a potential mechanism through which aerobic exercise can result in acute alterations within the core executive functions, under moderately stressful conditions.

More precisely, the available evidence indicates that acute stress engages the PFC in the service of adapting to the current situation. This engagement is characterized by changes in oxygenated cerebral blood flow that shift from regions of the PFC, which are commonly necessary in effortful behaviour, to those in other brain areas such as the amygdala, which are typically necessary for individuals to prepare the fight-or-flight response (for details, see: Dedovic et al., 2009; Pruessner et al., 2008). Within this line of reasoning, acute stressors are associated with reduced oxygenated blood flow within the PFC, which reflects a *cognitive shift*, to transition away from "thinking with effort", a process that generally involves executive functioning through the PFC, to "thinking fast", which generally involves the HPA axis as well as parts of the limbic system, in order to fight against or flee from the perceived stressor (Dedovic et al., 2009; Pruessner et al., 2008). Such *shifts* in how our immediate surrounding influence our cognition is adaptive in that stressor-related *decreases* in prefrontal oxygenation are intended to facilitate our fight-or-flight response. Yet, such a shift in cognitive processing may result in a deterioration in executive functions that involve the PFC, such as flexibility, inhibition, and working memory.

As mentioned previously, various forms of aerobic exercise, including stationary cycling (e.g., Endo et al., 2013; Li et al., 2014, 2019; Yanagisawa et al., 2010), may be associated with a

greater increase in prefrontal oxygenation during assessments for inhibition or working memory, in comparison to when the same tasks are performed following control conditions. Findings such as these support the view that acute participations in exercise generally regulate our responses to stress. Participations in exercise are associated with a cortisol response may lower over time such that a down-regulation of the HPA axis occurs concomitantly, with the act of exercising (Sothmann et al., 1996). Because the available evidence suggests that the PFC may have an inhibitory effect on activation of the HPA system (Dedovic et al., 2009), the above view suggests the potential for aerobic exercise to lead to acute increases in prefrontal oxygenation by individuals who perform executive function tasks under moderate psychosocial stress. If so, this view implies that various types of aerobic exercise may help individuals overcome the cognitive challenges, particularly those involving the core executive functions, that can arise as a result of experiencing acute psychosocial stress.

When evidence from the above literature is considered in unison with one another, it may be possible for aerobic exercise to regulate stressor-induced changes in flexibility, inhibition, and working memory through concentration changes in cortisol and cerebral flow within the PFC. As the above literature suggests, no known studies have assessed the interactive influence of aerobic exercise and psychosocial stress upon flexibility, inhibition, or working memory, and the relative involvement of the PFC during these situations. This gap in the literature is important because 1.) daily stress is pervasive to many Canadians (Statistics Canada, 2019); 2.) participating in aerobic activity has been recommended to manage stress (Diamond, 2015); and 3.) evidence supports the potential effectiveness of aerobic exercise for the management of stress (for example, see Dupuy et al., 2015; Klaperski et al., 2013; Li et al., 2019; Rimmele et al., 2007, 2009). Because stress is

unlikely to recede from day-to-day life, these topics of the literature are worth exploring in order to provide individuals with evidence-based resources to manage stress.

1.9 The Utility of Scoping Reviews

One way to accomplish this is from reviewing the literature to narrate, summarize, and/or evaluate the available evidence. Different forms of reviews may be performed in this respect, and the type of review selected depends on the research question(s), as well as the extent to which the researcher expects those questions to have been addressed, by the literature (Arksey & O'Malley, 2005; Badger et al., 2000; Peters et al., 2015). When an extensive number of articles are believed to have addressed a research question of interest, a systematic review of the literature is generally selected in order to restrict one's narrative of the literature to studies of a good quality (Badger et al., 2000; Centre for Reviews and Dissemination, 2009). With this approach, the resulting review reflects a systematic search of available evidence associated with the research questions, because the included studies are evaluated for study characteristics, findings of interest and the quality of methodology (Centre for Reviews and Dissemination, 2009). If limited articles are anticipated to address a research question, a scoping review is favourable in comparison to a systematic review (Arksey & O'Malley, 2005). This approach does not involve a systematic search of the literature, in that the included studies are summarized, in a manner that addresses the research question, but are not evaluated for quality (Arksey & O'Malley, 2005). By this manner one of the purposes for performing a scoping review is to summarize an emerging topic of extant literature. A systematic review might be then recommended if the findings from the scoping review reflected a sufficient number of studies, in order to assess evidence quality (Arksey & O'Malley, 2005).

2. Objectives

The aim of the present study was to conduct a scoping review of the literature to summarize evidence on the involvement of the PFC during stress- and aerobic exercise-related alterations in flexibility, inhibition and working memory. To this end, the current review was conducted in the service of addressing the following research questions:

i. How can psychosocial stress influence flexibility, inhibition, and working memory, and is this associated with activation changes in areas within the PFC, as assessed in studies that included diffusion tensor imaging, EEG, fMRI, fNIRS, MEG, PET, and/or a single-cell recording in their methodology?

ii. How can aerobic exercise influence flexibility, inhibition, and working memory, and is this associated with activation changes in regions within the PFC, as assessed in studies that included diffusion tensor imaging, EEG, fMRI, fNIRS, MEG, PET, and/or a single-cell recording in their methodology?

iii. What protocols have been used to induce an acute experience of psychosocial stress as well as aerobic exercise to understand the influence of these experiences, on flexibility, inhibition, and working memory, as assessed in studies which included diffusion tensor imaging, EEG, fMRI, fNIRS, MEG, PET and/or single-cell recording to investigate the involvement of the PFC under these circumstances?

iv. What assessments have been used to assess flexibility, inhibition, and working memory, in relation with the acute influences of experiencing moderate levels of aerobic exercise and/or psychosocial stress, as assessed in studies that included diffusion tensor imaging, EEG, fMRI, fNIRS, MEG, PET and/or a single-cell recording in their methodologies to investigate the involvement of the PFC under these circumstances?

3. Methods

3.1 Protocol

My procedure involved developing a search strategy, establishing my requirement for the inclusion of studies, performing my literature search, selecting studies for inclusion, provided the studies met the appropriate requirements for inclusion, charting the results from included studies, and synthesizing the results in a manner that addressed the objectives of my scoping review. As a further note, I conducted my scoping review in this manner, in accordance with guidelines within previous literature (Arksey & O'Malley, 2005; Peters et al., 2005). Figure 3 shows my procedure of selecting studies for inclusion and uses the Preferred Reporting Items for Systematic Reviews and Meta-analyses (PRISMA) diagram (Moher et al., 2009; Peters et al., 2005).

3.2 Literature Search

Following the recommendations from the Joanna Briggs Institute (Peters et al., 2015) and Arksey and O'Malley (2005), I selected multiple sources to retrieve articles. Within these aims, I performed an electronic search for potential articles using PubMed and PsycInfo. I selected these databases, as PubMed and PsycInfo are commonly used databases, to perform literature searches within the psychosocial stress literature (i.e. Dickerson & Kemeny, 2004; Shields et al., 2016a). I selected two databases to perform my literature search as the previously cited literature has stated that scoping reviews must, whenever possible, be performed, in at least two databases (Arksey & O'Malley, 2005; Peters et al., 2015). Because I speculated that my research objective represented emerging areas of the literature based on a literature review I also performed my literature search through additional sources as described below and in accordance with guidelines from previously cited literature (Arksey & O'Malley, 2005; Peters et al., 2015).

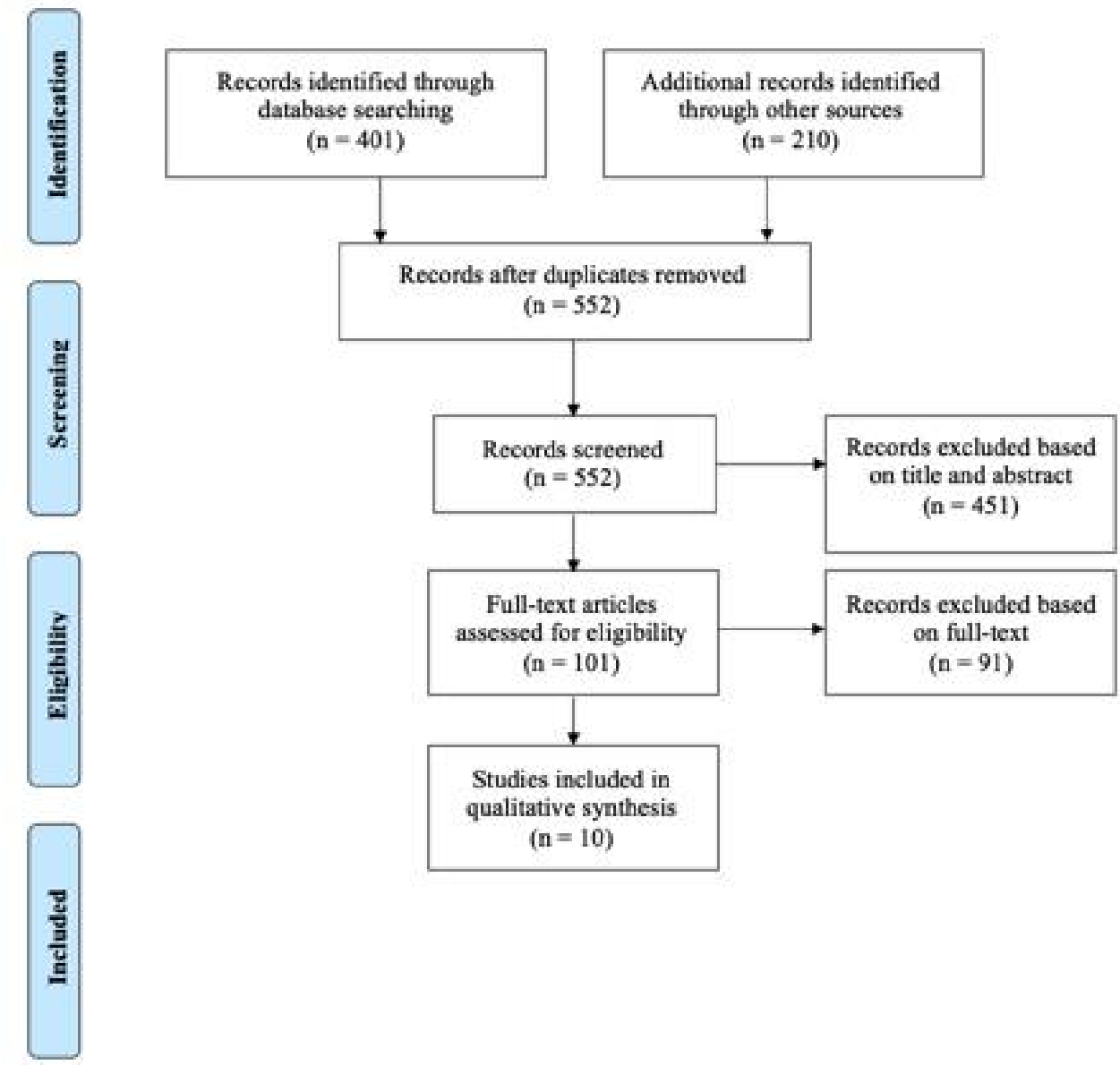

Figure 3. **PRISMA diagram.** Process of selecting articles for inclusion by applying criteria to the title and abstract of each. Articles that appeared eligible for inclusion based on this process were re-screened for eligibility by re-applying the appropriate criteria to its full-text.

I conducted an electronic literature search on PubMed and PsycInfo on June 7, 2020. For reference, Appendix **A** has details with respect to the search terminology and search restrictions I applied during my literature search, on PubMed and PsycInfo. Following guidelines from current

literature (Arksey & O'Malley, 2005; Centre for Reviews and Dissemination, 2009; Peters et al., 2015), I also performed my electronic search, through additional sources, between June 15, 2020 and June 16, 2020. I identified these articles, by searching the reference lists from a proportion of articles identified, from my database search. When the title and abstract for a study indicated that it was eligible for inclusion, I searched the references list of that article, for articles, that I did not retrieve, as a result of my database search. Over the course of this process, if a reference title was indicative of potential eligibility, the article was retrieved and screened for inclusion, through the process I have described in *Section 3.5*. These additional sources correspond to searching the list of references of each full-text article I assessed for eligibility, in Figure 3. Full-text articles that I assessed for eligibility are denoted with *, and those articles included in my qualitative synthesis are denoted with ** from the bibliography. Finally, the bibliography shows articles that were not retrieved from the literature search, but whose full-text indicated their eligibility for inclusion, as indicated by ***. Note that, though studies marked with *** in the bibliography are summarized in the discussion, these studies should be reviewed more extensively by future research.

3.3 Study Selection

Prior to performing my literature search, I determined search terms that I would utilize as I searched for articles on PubMed and PsycInfo. I determined search terminology, with the aid of the Psychology Librarian at Dalhousie University as well as with the help of the Subject-Specific Module at Dalhousie University, between June 4, 2020, and June 6, 2020. My procedure of study selection is shown by Figure 3. From the 552 articles that I retrieved from my literature search, 4 articles were included, from the psychosocial stress literature, with 6 included within the aerobic exercise literature.

3.4 Inclusion Criteria

For reference, details for my inclusionary criteria are in Appendix **B**. I developed similar requirements for the inclusion of articles, from the psychosocial stress literature, and the aerobic exercise literature, with some exceptions. For the purpose of this section, I refer to *manipulation,* with respect to the procedure employed to induce an acute state of psychosocial stress or aerobic exercise. With these mind, my requirements for the inclusion of studies are described below and in accordance with recommendation in the scoping review literature (Arksey & O'Malley, 2005; Peters et al., 2015) I also describe the reasons behind my inclusion criteria. For reference, please see *Section 3.4.1*.

To be eligible for inclusion, the study must have included humans, and/or nonhumans, as research participants. Within this criterion, articles with nonhuman participants initially qualified provided the research sample involved nonhuman primates. When humans served as participants, the article was eligible for inclusion, provided the study sample involved adults between the ages of 18 to 40, were of a good health status, and did not represent medical conditions, or medication use, known to influence the responsiveness of HPA axis, or PFC, in response to the experimental manipulation, as ascertained by the screening protocol reported during study recruitment.

To be eligible for inclusion, the manipulation must have lasted 1 h, or less. When it was applied as a within-subjects factor, the experimental and control condition for the manipulation must have been separated by a minimum of 24 h. An article must have also assessed flexibility, inhibition, and/or working memory in a pre-post manner, relative to the manipulation. As such, when the manipulation served as a within-subjects factor, the above component(s) of executive functioning must have been assessed, following each cessation of the experimental and control conditions for the manipulation. When the manipulation was a between-subjects factor a study

was eligible for inclusion, provided that the above component(s) of executive functioning was assessed, before the onset and following the cessation of the manipulation. For an article to be eligible for inclusion, PFC functioning must have been recorded during cognitive assessments with the use of DTI, EEG, fMRI, fNIRS, MEG, PET, and/or single-cell recording. Within the criterion above, regions of the PFC must have shown manipulation-induced patterns of either activation and/or deactivation during cognitive assessment.

Unique to articles identified through the psychosocial stress literature, the manipulation must show evidence, in its ability to activate the HPA axis. With this criterion, we necessitated that the manipulation either within the article in question or from other articles in the literature, has been reported to increase salivary cortisol levels in healthy human adults between the ages 18 to 40. Unique for articles retrieved through the aerobic exercise literature, the manipulation must show evidence of moderate intensity, for each individual tested. Within this criterion, we necessitated the manipulation intensity met one of the following: 40-60% of heart rate reserve, 50-75% of maximal oxygen re uptake, 50-75% of maximal heart rate, or the equivalent. When retrieved articles seemed eligible for inclusion, but applied an exercise intensity other than the intensities described above, the final decision was made, in consultation with our independent reviewer and, when necessary, the rest of our research team.

3.4.1 Criteria Justification

For the current review, I required nonhuman primates and human adults of a good health status, free of any medical condition and medication use that may influence stress- and exercise-induced responses of the HPA axis and PFC, and between 18 and 40 years of age, at the time of testing for the following reasons. Beginning with nonhuman primates, I included such a species, based on evidence that proposes the PFC in nonhuman primates responds to psychosocial stress

through a functionally similar manner as that observed for human adults (Sanchez et al., 2015; Spinelli et al., 2014). Receptors for glucocorticoid are abundant in areas of the PFC, in various monkey species (for a review, see Sanchez et al., 2015) and acute influences of a psychosocial stressor have been studied in these species, on the assumption that these stressors (often in the form of separating young monkeys from their mothers; for reference, see Spinelli et al., 2014) influence the HPA axis and PFC.

Turning to human adults I required that the research participants were free of any medical conditions and medication use which may influence the stress- and exercise-induced responsivity from the HPA axis and PFC. I included this criterion based on evidence that proposes that human adults respond differently from one another during psychosocial stress (for a review, see Dedovic et al., 2009; Zänkert et al., 2019) and physical exercise (for a review, see Brisswalter et al., 2002; Kashihara et al., 2009; Sothmann et al., 1996). Moreover, such inter-individual differences in the above responses may depart from what we expect when HPA axis and/or PFC function becomes affected from medical condition or medication use. Turning to my age range criterion, I required articles to exclude adults 41 years or older at the time of testing based on evidence that proposes that HPA axis (Zänkert et al., 2019) and PFC (McEwen & Morrison, 2013) function can change, with increasing age. Because the available evidence suggests that the PFC can mature around 18 years of age and begins to decline in middle adulthood, which may roughly correspond to adults in their early 40s, the 18-40 age range criterion was selected, for this reasoning (Diamond, 2002; McEwen & Morrison, 2013).

Due to limited time and limited resources, I only included articles if published in English. As Appendix **A** suggests, I also restricted my literature search to publications between January 1, 1990 and June 7, 2020. I selected the year of 1990 as the TSST (Kirschbaum et al., 1993), which

is considered as the gold standard for acute manipulations of psychosocial stress (for review, see Dickerson & Kemeny, 2004; Zänkert et al., 2019), was published during 1993. Moreover, I have selected manipulations for psychosocial stress 1 h or less in duration and were previously shown to increase salivary cortisol responses, as manipulations that included these elements, such as the TSST (Kirschbaum et al., 1993), have been recommended to be used to manipulate an acute state of psychosocial stress in participants (for a meta-analysis, see Dickerson & Kemeny, 2004). With respect to manipulations for aerobic exercise, I required the duration and intensity described (See *Section 3.4* for details) based on guideline from the American College of Sports Medicine (2014) in addition to my own familiarity, with the literature. Finally, I included numerous neuroimaging modalities for the inclusion of studies, because DTI, EEG, fMRI, fNIRS, MEG, PET, and single-cell recording provide different, and at times complementary, information, with respect to neural activity in the brain (for a discussion, see Bunce et al., 2009).

When manipulations of psychosocial stress or aerobic exercise served as a within-subject factor, I required that participants performed each condition of the manipulation with a minimum of 24 h that separated performing one condition from the other. I selected this criteria based upon evidence that indicates that, when the concentration of salivary cortisol increases as a response to external stressors, concentration changes in cortisol may take upto 24 h to return to the level, that was observed pre-stress (Shields et al., 2016a). Finally, to reassure that the included articles have observed stressor- or exercise-induced *changes* in flexibility, inhibition, and/or working memory, the assessment of executive functioning must have been evaluated using a pre-post manner, with respect to the manipulation (Shields et al., 2016a). When such manipulation served as a repeated-measures factor, flexibility, inhibition, and/or working memory must have been evaluated before the onset and following the cessation of psychosocial stress or aerobic exercise. In comparison, a

study, in which manipulations of psychosocial stress or manipulations of aerobic exercise served as a between-subjects factor, assessments of flexibility, inhibition, and/or working memory must have been evaluated following the cessation of each condition of the manipulation. To reassure a potentially included study reported stress- or exercise-induced changes in PFC function while the participants performed assessments for flexibility, inhibition and/or working memory, DTI, EEG, fMRI, fNIRS, MEG, PET, and/or single cell recordings must have been acquired during each test of flexibility, inhibition, and/or working memory.

3.5 Data Abstraction

Following my literature search, an independent reviewer included articles, from applying our inclusion criteria. For reference, Appendix **B** shows the instructions with which the reviewer was provided. Briefly, we instructed our reviewer to determine article eligibility by applying the appropriate criteria, to the title and abstract to each article. In cases when article eligibility could not be determined from the title and abstract, the full-text article was retrieved, and the inclusion criteria was applied to the introduction, method, results, discussion, and, where necessary, to the supplementary materials. We met with our reviewer in the form of a virtual meeting, on June 28, 2020, where we clarified any questions about our inclusion criteria. Following this, our reviewer selected articles for inclusion between June 30, 2020 and July 13, 2020. We corresponded again through email on July 13, 2020 where we made the final decision on articles that were excluded by one reviewer but included by the other. Our final decision led to the inclusion of 4 articles in the psychosocial stress literature and 6 articles in the aerobic exercise literature, for a total of 10 articles.

3.6 Data Charting

Following study selection, I summarized information from all eligible articles, in relation to each research question. The information was summarized in a table format, through Microsoft Excel. For reference, these tables are shown in Appendix **C** and Appendix **D**. These tables show my summary of the following study characteristics and findings:

i. Author name(s) and publication year;
ii. Sample size, and, in cases when a study included males and females, the sex distribution, expressed in numerical values;
iii. Among females, whether their menstrual cycle phase, and/or oral contraceptive use, were reported and, if so, whether these were controlled for, in relation to stress responsiveness;
iv. Protocol applied to induce an acute state of aerobic exercise and/or psychosocial stress, including protocol duration, expressed in minutes;
v. Whether aerobic exercise and/or psychosocial stress was a between-subjects or a within-subjects variable;
vi. In cases where aerobic exercise and/or psychosocial stress served a within-subjects factor the inter-session interval reported in association with when each condition was performed expressed in days;
vii. PFC regions of interest;
viii. Neuroimaging modality used to record PFC-related activation and/or deactivation during assessments of flexibility, inhibition and/or working memory irrespective of the literature area from which the selected article was retrieved;
ix. Whether flexibility, inhibition, and/or working memory was assessed;

x. Assessment(s) used to assess flexibility, inhibition, and/or working memory and the time lag between cognitive testing, from the cessation of aerobic exercise and/or psychosocial stress, expressed in minutes;

xi. Stress- and/or exercise-induced changes in the behavioural measures recorded during the assessments of flexibility, inhibition, and/or working memory;

xii. Stress- and/or exercise-induced patterns of activation and/or deactivation in regions of the PFC during assessments of flexibility, inhibition, and/or working memory.

3.7 Data Analyses

Given that scoping reviews commonly involve a qualitative synthesis of current literature (Arksey & O'Malley, 2005; Peters et al., 2015), my results involved extracting information, from my data charts, and describing those that answered my research questions. To this aim, I chose to structure my **Results** in two sections. The first section summarized the findings from the selected articles from the psychosocial stress literature and the second section summarized those extracted from the aerobic exercise literature.

3.8 Data Synthesis

An aim of the present review was to perform a scoping review to summarize the available evidence in the involvement of the PFC in stressor- as well as aerobic exercise-related changes in flexibility, inhibition and working memory. In addition to summarizing findings from the studies included in this review, these findings were synthesized in the form of a data synthesis. Here, the involvement of specific regions within the PFC were labelled in the human brain in relation with localizing PFC regions which, based on findings from the included studies, may be involved in a person's capacity to use his or her executive functioning, following acute stress, or after an acute bout of aerobic exercise. By doing so, results from the included studies were visualized in a way

that attempted to delineate PFC regions that may be targeted by acute stressors, PFC regions that may be targeted by acute aerobic exercise, as well as PFC regions which appear targeted by both acute stressors and acute aerobic exercise. These are illustrated in Figure 4.

4. Results

My screening procedure is shown by Figure 3. I identified 401 studies through searching PsycInfo and PubMed, and an additional 210 articles were identified through sources, other than these databases. For the 401 findings from our database search, 247 articles were associated with the acute influence of psychosocial stress on flexibility, inhibition, and/or working memory. The remaining 154 studies were associated with the acute influence of aerobic exercise on flexibility, inhibition, and/or working memory. Of the 210 articles retrieved through additional sources, 177 of these were associated with the acute influence of psychosocial stress on flexibility, inhibition, and/or working memory, and the remaining 33 articles were associated with the acute influence of aerobic exercise on these components of executive functioning.

Of the 552 results retrieved from my literature search on PubMed, PsycInfo, and through additional sources, I excluded 451 articles after applying my inclusion criteria to the title as well as abstract of each. These articles were excluded for violating at least one criterion. As Figure 3 suggests, a total of 101 articles initially appeared eligible for inclusion, based on the title as well as abstract of each. After applying my inclusionary criteria to the full-text for each, a total of 10 articles were eligible for inclusion. This is shown in Table 1, Appendix **C**, and Appendix **D**.

Table 1. **Summary of findings from the included literature**.

			Stress						
			Study Characteristics				Outcomes		
Study	*N*	Stressor	Control	Task Type	Neuroimaging	PFC ROIs	Behavioural Outcomes	Neural Correlates	
Chang et al. (2020b)	30	TSST	TSST alone	Stop-signal	fMRI	superior/medial frontal gyrus	↑ response time, ≈ response accuracy	↑ bilateral superior/medial frontal gyrus	
Luethgau et al. (2018)	34	TSST	Read alone	0-, 2-back	fMRI	dorsolateral PFC	≈ response time, ≈ response accuracy	↓ right dorsolateral PFC	
Qin et al. (2009)	29	Violent film	Neutral film	0-, 2-back	fMRI	ACC, OFC, dorsolateral PFC	≈ response time, ≈ response accuracy	↑ ACC, ↓ bilateral dorsolateral PFC	
Van Aast et al. (2016)	21	TSST	Write alone	2-, 3-back	fMRI	dorsomedial, dorsolateral, ventromedial PFC	↓ response time, ≈ response accuracy	↓ dorsomedial PFC, ↓ dorsolateral PFC	
			Aerobic Exercise						
			Study Characteristics				Outcomes		
Study	*N*	Exercise	Control	Task Type	Neuroimaging	PFC ROIs	Behavioural Outcomes	Neural Correlates	
Endo et al. (2013)	13	Cycling	Seated rest	Stroop	fNIRS	dorsolateral PFC	↑↓ response time, ≈ response accuracy	↑↓ dorsolateral PFC	
Faulkner et al. (2016)	17	Cycling	Seated rest	Stroop	fNIRS	dorsolateral PFC	↓ response time, × response accuracy	↑ dorsolateral PFC	
Hwang et al. (2019)	30	Walking	Seated rest	Go/NoGo	EEG	medial PFC	× response time, ≈ response accuracy	↓ medial PFC	
Li et al. (2014)	15	Cycling	Seated rest	0-, 1-, 2-back	fMRI	ACC, left FG, left IFG, right LG, right MFG	≈ response time, accuracy	↓ ACC, left IFG, ↑ left FG, right LG, right MFG	
Ochi et al. (2018b)	15	Cycling	Seated rest	Stroop	fNIRS	left dorsolateral PFC	↑ response time, ↓ response accuracy	↓ left dorsolateral PFC	
Yanagisawa et al. (2010)	20	Cycling	Seated rest	Stroop	fNIRS	left dorsolateral PFC	↓ response time, ↑ response accuracy	↑ left dorsolateral PFC	

Note. *N* represents sample size; fMRI represents functional magnetic resonance imaging; fNIRS represents functional near-infrared spectroscopy; EEG represents electroencephalography; under PFC ROIs which represents the prefrontal cortical regions of interest, the ACC indicates anterior cingulate cortex; OFC presents the orbitofrontal cortex; FG indicates fusiform gyrus; IFG refers to the inferior frontal gyrus; LG represents lingual gyrus; and MFG represents the medial frontal gyrus. Under outcomes, ↑ response time indicates slower response times; ≈ response accuracy is an indicator of a similar response accuracy; ↓ response time indicates quicker response times; ↑↓ response time indicates both fast and slow response time, depending on exercise intervention; × indicates that behavioral measure indicated was not reported; under neural correlates, ↑ indicates increased activation in the indicated PFC region, as assessed by the neuroimaging modality used; ↓ indicates decreased activation in the indicated PFC region. All outcomes are summarized, with respect to the findings reported following the stress manipulation relative to control.

4.1 Acute Effects of Psychosocial Stress on Executive Functioning

Among the 552 articles that resulted from my literature search, I included 4 articles based on our inclusionary criteria (Chang et al., 2020b; Luettgau et al., 2018; Qin et al., 2009; Van Ast et al., 2016). The study characteristics and findings from these articles are summarized by Table 1, and a comprehensive summary of these articles are in Appendix **C**. Of the 552 articles, a total of 186 articles were identified through PsycInfo, 61 articles through PubMed, and we identified 177 articles through additional sources. Most pertinent for our research questions, each of the 4 included articles are described below, with respect to their procedure applied to induce an acute state for psychosocial stress, the task administered to examine flexibility, inhibition, or working memory, as well as the behavioural and neural findings reported.

Turning to my first research question, I asked what procedures have been applied, for the induction of psychosocial stress in investigations of its effects upon flexibility, inhibition and/or working memory. With this end, I observed that 3 of the 4 selected articles (Chang et al., 2020b; Luettgau et al., 2018; Van Ast et al., 2016) used variants for the TSST (Kirschbaum et al., 1993) to produce an acute state of psychosocial stress. The remaining article used a selection of violent scenes from the film, Irréversible (2002) by Gaspar Noé, to produce acute psychosocial stress in participants (Qin et al., 2009).

Turning to my second research question, I asked which assessments have been applied to test flexibility, inhibition, and/or working memory, among the included articles. With this end, I observed that, 3 out of 4 included articles (Luettgau et al., 2018; Qin et al., 2009; Van Ast et al., 2016) used numeric variations of *n*-back for the assessments of working memory. Luettgau et al. (2018) and Qin et al. (2009) used 0- and 2-back, whereas Van Ast et al. (2016) applied 2- and 3-back to assess working memory. Finally, Chang et al. (2020b) applied the stop-signal test in the assessment of inhibition.

Returning to my remaining research questions, the remainder of this section describes the behavioural outcomes and neural correlates for stress-induced changes in inhibition and working memory, as ascertained, using fMRI (Chang et al., 2020b; Luettgau et al., 2018; Qin et al., 2009; Van Ast et al., 2016). I start by describing the finding reported by Chang et al. (2020b) in which stress-induced changes in inhibition were reported and I then summarize the results for the other 3 studies, in which stressor-induced changes for working memory were reported (Luettgau et al., 2018; Qin et al., 2009; Van Ast et al., 2016).

To begin, Chang et al. (2020b) found that the TSST was associated with quicker response times in trials when a *stop* cue shortly followed a *go* cue, in comparison to the findings observed

following the control non-stressful situation. Response accuracy did not differ between the stress and control groups during these trials (Chang et al., 2020b). With trials when response inhibition was not required in order to perform the stop-signal task well, response time, as well as response accuracy, did not differ between the stress and control groups. Moreover, stress-induced changes in reaction times during *stop* trials were associated with increased BOLD contrast within the left and right medial frontal gyrus as well as in the left and right superior frontal gyrus.

Returning to working memory, Luettgau et al. (2018) as well as Qin et al. (2009) did not observe stress-induced changes in reaction time or response accuracy during 0- and 2-back. Yet in both studies, decreased BOLD contrast in the dorsolateral PFC was observed for participants who performed 2-back, although not when the 0-back was performed, following stress, relative to the findings observed, following the control, non-stressful condition. In addition, Qin and co-workers found increased BOLD contrast for the anterior cingulate cortex, with participants who performed 2-back in-between viewing violent movie scenes, in comparison to when 2-back was completed in-between viewing neutral movie scenes. Using 2- and 3-back Van Ast et al. (2016) found that a modified TSST (Kirschbaum et al., 1993) was associated with an increased BOLD contrast in the ventromedial PFC, but a decreased BOLD contrast in the dorsomedial as well as the dorsolateral PFC, in participants who performed 2- and 3-back in comparison to when 2- as well as 3-back was performed, prior to stress onset. At the behavioral level, the modified TSST was associated with slower response times whereas response accuracy remained unaffected, by participants who performed 2- as well as 3-back in comparison to when such assessments were performed prior to stress onset (Van Ast et al., 2016).

4.2 Acute Effects of Aerobic Exercise on Executive Functioning

From the 552 articles which resulted from my literature search I included 6 articles based on my inclusionary criteria (Endo et al., 2013; Faulkner et al., 2016; Hwang et al., 2019; Li et al., 2014; Ochi et al., 2018b; Yanagisawa et al., 2010). The study characteristic as well as the results reported in the selected articles are summarized in Table 1. For a comprehensive summary, refer to Appendix **D**. Of the 552 results, 74 articles were retrieved through PsycInfo, 80 from through PubMed, and 33 articles were retrieved using additional sources. Most pertinent for my research questions, I describe how each of the included articles, induced an acute participation in aerobic exercise, the task administered to assess flexibility, inhibition, and/or working memory, and the behavioural as well as neural findings reported.

Turning to my research question, I asked what protocols have been utilized, during acute manipulations of aerobic exercise. To this end, I found that 5 of the 6 articles applied stationary cycling (Endo et al., 2013; Faulkner et al., 2016; Li et al., 2014; Ochi et al., 2018b; Yanagisawa et al., 2010), whereas the remaining article employed treadmill walking (Hwang et al., 2019) to induce an acute participation in aerobic exercise.

Returning to my next research question I asked how flexibility, inhibition and/or working memory was assessed. To this end, I found that Ochi et al. (2018b) and Yanagisawa et al. (2010) administered congruent, incongruent, and neutral conditions for a modified Stroop task. Endo et al. (2013) and Faulkner et al. (2016) only administered congruent and incongruent conditions of a modified Stroop task, and Hwang et al. (2019) administered a modified Go/NoGo task. As the list above suggests, the included studies differed in the assessment used to test inhibition, where most of these studies (4 of 5) used a modified Stroop task. With respect to working memory, Li et al. (2014) used 0-, 1-, and 2-back.

To begin, Li et al. (2014) found increased BOLD contrast in the anterior cingulate cortex, right paracentral lobule and left inferior frontal gyrus in women that performed 2-back following 20 min of cycling at 60-70% maximal heart rate in comparison to women who participated in 30 min of seated rest. In addition, Li et al. (2014) found a decreased BOLD contrast within the right medial frontal gyrus, right lingual gyrus, and the left fusiform gyrus, for those who performed 2-back following 20 min of cycling at 60-70% maximal heart rate in comparison with women who participated in 30 min of seated rest. None of the above PFC regions revealed changes in BOLD contrast in participants who performed 0- or 1-back following aerobic exercise in comparison to 30 min of seated rest (Li et al., 2014). Response times as well as response accuracy did not vary in participants who performed 0-, 1-, or 2-back following aerobic exercise in comparison to rest (Li et al., 2014).

Turning to inhibition, Endo et al. (2013) found faster response times, for participants who performed the incongruent and congruent trials for a modified Stroop task, following 15 mins of cycling at 40% maximal voluntary intensity in comparison to when the test was performed, after 15 min of seated rest. In a similar manner, Endo et al. (2013) found faster response times among participants who performed the Stroop task after 15 min of cycling at 60% maximal intensity, in comparison to when the task was performed following 15 mins of seated rest. Group differences in response accuracy, were not found. Finally, an exercise-induced increase in the concentration of oxygenated hemoglobin in the dorsolateral PFC was found in participants who performed the modified Stroop test following cycling at 40% maximum voluntary intensity (Endo et al., 2013). By comparison, an exercise-induced decrease in the concentration of oxygenated hemoglobin in the dorsolateral PFC was found in participants who performed the Stroop task following cycling at 60% maximal voluntary intensity (Endo et al., 2013). Altogether, these findings support those

reported by Faulkner et al. (2016) with a sample of males. More precisely, Faulkner et al. (2016) found increased oxygen saturation in the dorsolateral PFC in men who performed congruent and incongruent trials during a modified Stroop test following 30 min of cycling at 45-60% maximal oxygen reuptake in comparison to males who performed the test following 30 min of seated rest. Though Faulkner et al. (2016) did not report response accuracy, participants demonstrated faster response times, when the Stroop task was performed following 30 min of cycling in comparison to when the task was performed following 30 min of seated rest.

Using a Japanese variation of the Stroop task, Yanagisawa et al. (2010) found both faster response times, as well as greater response accuracy, in participants who performed incongruent trials of the task following 10 min of cycling at 50% maximal oxygen reuptake in comparison to participants who performed incongruent trials following 15 mins of seated rest. Participants also showed an exercise-induced increase in the concentration of oxygenated hemoglobin for the left dorsolateral PFC, while performing incongruent trials, which was also associated with the faster response times observed, during these trials (Yanagisawa et al., 2010). Using a similar variation of the Stroop task, as Yanagisawa et al. (2010), Ochi et al. (2018b) found slower response times as well as reduced response accuracy in participants that performed incongruent trials following 10 min of cycling at 50% maximal oxygen reuptake under hypoxic conditions, in comparison to participants who performed the trials following 15 min of seated rest. Hypoxic-induced exercise was also associated with a decreased concentration with oxygenated hemoglobin, within the left dorsolateral PFC, for participants who performed incongruent trials (Ochi et al., 2018b). Ochi et al. (2018b) also observed that, the hypoxic exercise-induced reduction with the concentration of oxygenated hemoglobin in the left dorsolateral PFC for participants who performed incongruent

trials of the modified Stroop test was associated with the slower response times observed during these trials.

Finally, Hwang et al. (2019) found a similar response accuracy in women who performed a modified Go/NoGo task following 20 min of walking at 70-75% maximal heart rate relative to women who performed the task, following 20 min of seated rest. Hwang et al. (2019) also found decreased N2 amplitude in the medial PFC for women who performed *NoGo* trials, in which one needed to withhold from responding following the presentation of a sad face, in association with the findings observed in women who performed these trials following 20 min of seated rest. The study did not report exercise-induced changes in EEG activation other than that of N2 amplitude nor were response times during the Go/NoGo task reported (Hwang et al., 2019).

4.3 Synthesis of PFC Findings

As the **Objectives** suggest, this study was interested in the neural corelates of stressor- as well as exercise-induced changes for flexibility, inhibition, and working memory. Based on data summarized from the included literature, Figure 4 summarizes these findings, within the context of the broader literature. With a similar manner, Figure 5 summarizes findings from the exercise literature included in this review within the context of the broader literature, and is consequently intended to complement the bottom panel of Figure 4.

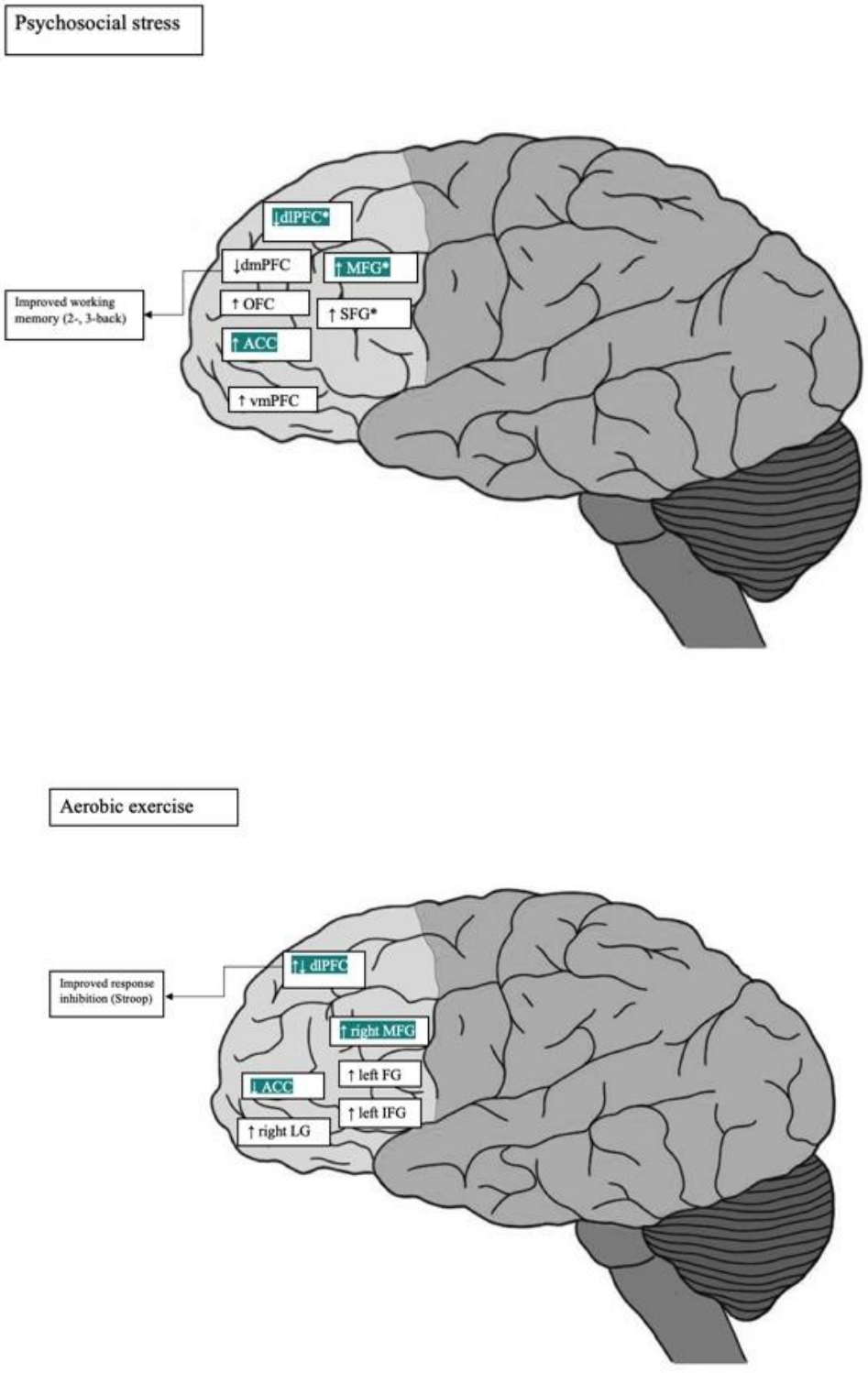

Figure 4. **Inhibition- and working memory-related PFC activation**.

Note. dlPFC represents dorsolateral PFC; dmPFC represents dorsomedial PFC; OFC represents the orbitofrontal cortex; SFG represents the superior, frontal gyrus; ACC represents the anterior cingulate cortices; vmPFC represents the ventromedial PFC; IFG refers to inferior frontal gyrus. This figure represents the relationships between activation in areas of the PFC and activation of the HPA axis as reported by PET (Kern et al., 2008; Pruessner et al., 2008) and fMRI (Dedovic et al., 2009; Eisenberger et al., 2007; Wang et al., 2005; Wheelock et al., 2016; Zschucke et al., 2015) during acute manipulations of psychosocial stress or aerobic exercise. ↑ represents that a positive relationship was reported whereas ↓ represents a negative relationship was reported by the above literature (Dedovic et al., 2009; Eisenberger et al., 2007; Kern et al., 2008; Pruessner et al., 2008; Wang et al., 2005; Wheelock et al., 2016; Zschuke et al., 2015). This illustrates the findings summarized from the included literature, within the context of broader literature. Here, PFC regions highlighted in teal (i.e., dlPFC) that those PFC regions showed stressor- as well as aerobic exercise-related changes in activation during tasks of inhibition or working memory by studies included in the present review.

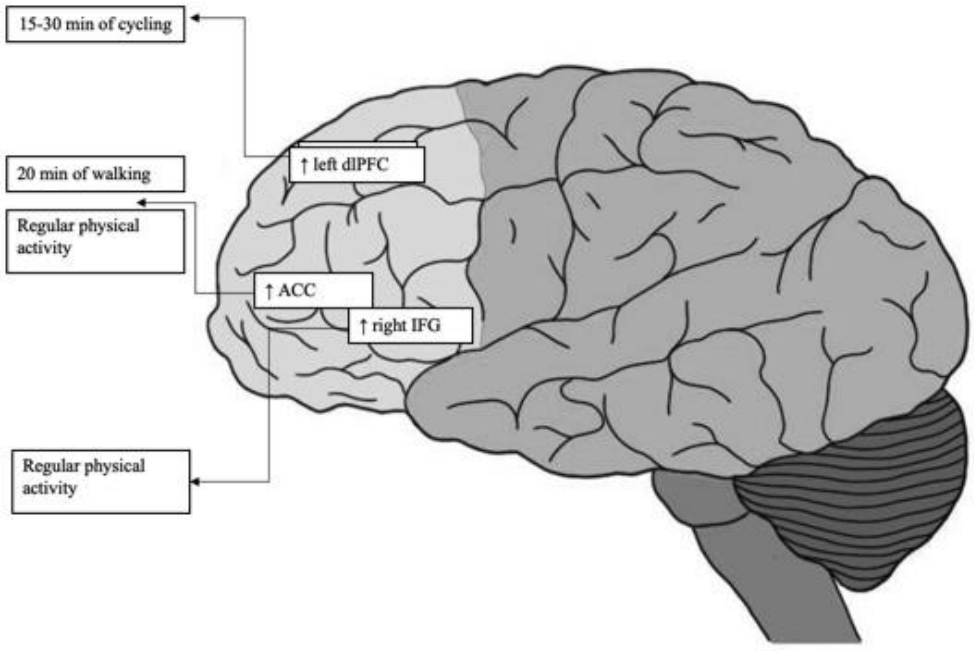

Figure 5. **Exercise-related changes in PFC oxygenation during executive functioning**.

Note. dlPFC represents the dorsolateral PFC; ACC represents the anterior cingulate cortices; IFG represents the inferior frontal gyrus; This figure shows how regular physical activity, as assessed by the maximal oxygen reuptake values achieved during a graded maximal exercise test, or acute bouts of physical activity, as induced by 15-30 min of walking or cycling, is associated with PFC oxygenation among the labelled region (Dupuy et al., 2015; Li et al., 2014, 2019; Yanagisawa et al., 2010). ↑ represents an increase in oxygen in the labelled PFC region, as assessed with fNIRS, as participants either performed incongruent trials for a modified Stroop Task (Yanagisawa et al., 2010) or 2-back (Li et al., 2014, 2019). This figure represents the results reported, from studies I included in my scoping review (Li et al., 2014; Yanagisawa et al., 2010), as well as from studies within the context of the broader literature (Dupuy et al., 2015; Li et al., 2019).

5. Discussion

The aim of the present study was to conduct a scoping review of the literature, in relation to the acute influence of psychosocial stress, as well as the acute influence of aerobic exercise on the flexible, inhibitory, and working memory aspects of executive functioning. More precisely, I was interested in how acute experiences of psychosocial stress, as well as how acute experiences of aerobic exercise, influence PFC functioning, while individuals perform tasks that predicate on flexibility, inhibition, and/or working memory. At a general level, I found the PFC is involved in various tasks that require flexibility, inhibition, and working memory, following the cessation of psychosocial stress or aerobic exercise. The following sections discuss these results with respect to the current literature and recommendations are provided for future research.

5.1 Reasons for the Exclusion of Studies from the Aerobic Exercise Literature

Prior to discussing the results from the included studies within the context of the broader literature, it is worth noting the reasons for the exclusion of studies during study selection. Over the course of study selection, those that examined aerobic exercise-related changes in executive functioning were primarily excluded for not including any type of neuroimaging to evaluate the involvement of the PFC. Some of these studies are shown in Appendix **E**. Other reasons for the exclusion of studies from the aerobic exercise literature included the observation that neither of flexibility, inhibition, or working memory was assessed; the observation that an acute period of aerobic exercise of moderate intensity, did not characterize the exercise intervention; and/or the observation that, in cases when flexibility, inhibition, or working memory was assessed, a study did not assess exercise-induced changes in executive functioning using a pre-post manner, such that flexibility, inhibition, or working memory was assessed following the cessation of exercise but was not assessed beforehand.

5.2 Reasons for the Exclusion of Studies from the Psychosocial Stress Literature

Likewise, it is worth noting the reasons for the exclusion of studies from the psychosocial stress literature. Here, those that examined stress-induced changes in executive functioning, were primarily excluded for not evaluating flexibility, inhibition, or working memory (see Appendix **E** for a list for some of these citations). Other reasons for study exclusion, were the observation that stressor-related changes flexibility, inhibition, or working memory were not assessed using a pre-post manner, such that the executive function investigated was evaluated, following the cessation of stress induction, but was not assessed beforehand (or, in cases when the stressor was used as a between-subjects factor, executive functioning was unassessed, following the cessation of the no stress control condition); the observation that a study did not involve neuroimaging; and, in what seemed to be case for multiple studies, the observation that the stress induction method was not a standardized laboratory stressor, in that the method employed, was not previously shown to elicit an increase in cortisol release.

5.3 Protocols to Induce Psychosocial Stress

In the present review, I found that most of the included articles applied modified versions for the TSST (Kirschbaum et al., 1993) to manipulate an acute state of psychosocial stress. More precisely, Chang et al. (2020b), Luettgau et al. (2018), as well as Van Ast et al. (2016) employed modified versions for the TSST (Kirschbaum et al., 1993), whereas Qin et al. (2009) employed a selection of violent scenes from the film, Irréversible by Gaspar Noé, to induce acute stress. This finding is consistent with the literature. More precisely, evidence from behavioural (Childs & De Wit, 2014; Juster et al., 2015; Mordecai et al., 2015; Obasi et al., 2017) and from fMRI (Antal et al., 2014; Buchanan et al., 2009, 2010; Eisenberger et al., 2007) studies indicates that a modified version of the TSST (Kirschbaum et al., 1993) is commonly used, for inductions of psychosocial

stress in healthy adults. Likewise, modified versions of the TSST (Kirschbaum et al., 1993) have been applied in studies, that used other neuroimaging modalities as well, such as those involving PET (Kern et al., 2008) and fNIRS (Rosenbaum et al., 2018). With respect to the use of violence from films to induce acute psychosocial stress in participants, studies that utilized Irréversible by Gaspar Noé represent a research group at Radboud University in the Netherlands.

More precisely, Qin and co-workers (for example, see Ossewaarde et al., 2011; Qin et al., 2009, 2012; van Marle et al., 2009, 2010) commonly selected violent scenes from Irréversible by Gasper Noé to induce acute stress, in participants. Here, it is more appropriate to consider the act of seeing violent movie clips, as emotional stress, rather than psychosocial stress. As Qin and co-workers have explained, participants are often instructed to imagine themselves as witnessing the violence depicted from the film, and participants are recruited on the assumption that they do not regularly watch violent movies (Qin et al., 2009). As such, seeing a violent film was presumed to induce acute stress, in that a participant may feel that the violence he or she sees is novel, as well out of his or her control, and hence encompasses the components of novelty and uncontrollability used by earlier definitions of stress (Mason, 1968). While this form of stress does not manipulate feelings of negative social evaluation from figures of authority in comparison to variations of the TSST (Kirschbaum et al., 1993) or MIST (Dedovic et al., 2005), it is still associated with greater salivary cortisol responses, in comparison to participants who view scenes without violence (Qin et al., 2009).

5.4 Protocols to Induce Aerobic Exercise

In the present review, I found that most of the included articles applied modified versions of cycling to induce an acute participation in aerobic exercise. More precisely Endo et al. (2013), Faulkner et al. (2016), Li et al. (2014), Ochi et al. (2018b) as well as Yanagisawa et al. (2010) all

used cycling to induce an acute participation in aerobic exercise, although the precise duration of cycling varied across studies, whereas Hwang et al. (2019) utilized self-paced walking, to induce aerobic exercise. This is somewhat supported by extant literature. More precisely, evidence from behavioural (Alves et al., 2012; Chang et al., 2011; Wang et al., 2015) and fMRI (Li et al., 2019) studies suggests that modified versions of walking or cycling are commonly used to induce acute aerobic exercise in healthy adults. At the same time, past literature has also employed the graded exercise test to examine the acute influences of aerobic exercise upon executive functioning. For instance, Themanson and Hillman (2006) applied a graded maximal exercise test, to evaluate the acute influences of aerobic exercise on response times and response accuracy, during the Eriksen flanker test (Eriksen & Eriksen, 1974). Likewise, one fMRI study also applied a graded maximal exercise test to evaluate the acute influences of aerobic exercise on response times, and response accuracy, during 0-, 1-, and 2-back as a function of aerobic fitness (Li et al., 2019).

The use of the graded maximal exercise test to evaluate the influences of aerobic exercise on inhibition (Themanson & Hillman, 2006) and working memory (Li et al., 2019) indicates past investigations on the influences of regular aerobic exercise on executive functions. As Li and co-workers (2019) have explained regular participations in aerobic exercise can influence a person's response to acute periods of aerobic exercise on executive functioning. More precisely Li and co-workers (2019) found that those who participated in regular aerobic exercise, as ascertained by a mean maximal oxygen reuptake value of 26.50 ml/kg/min during a graded maximal exercise test, showed a greater BOLD contrast in the left anterior cingulate cortex, in comparison to those who were less physically active as ascertained with a mean maximum oxygen reuptake value of 19.86 ml/kg/min, during the graded maximal exercise test. These findings were observed, in relation to the patterns of brain activation observed, while participants performed 2-back, following the end

of 20 min of cycling at 60-69% heart rate reserve, in comparison to the findings reported after 30 min of seated rest (Li et al., 2019). At a broader level, these results provide evidence for the view that aerobic fitness, also referred to as cardiorespiratory fitness within the literature (for example, see Li et al., 2019), regulates the effects of acute aerobic exercise on inhibition, in that those who show a greater blood flow and oxygen consumption during exercise, also show increased oxygen in the PFC in comparison to those who are less able to pump blood flow and oxygen.

With respect with inhibition the graded maximal exercise test has also been employed for the assessments of the acute influences of aerobic exercise on executive functioning. Themanson and Hillman (2006) found that those with a higher aerobic fitness, as ascertained from an average maximal oxygen reuptake value of 56.3 ml/kg/min, showed a greater P_e amplitude in comparison to those with lower aerobic fitness, as ascertained through an average maximum oxygen reuptake value of 38.7 ml/kg/min, during a graded maximal exercise test. These findings were observed in relation with the EEG activity observed over areas of the anterior cingulate cortex as participants demonstrated errors during the Eriksen flanker task (Eriksen & Eriksen, 1974) following the end of the graded maximal exercise test, in comparison to performing the Eriksen flanker task after a 30 min period of seated rest (Themanson & Hillman, 2006). Together, the above literature points to how the graded maximal exercise test has been used to evaluate the influence of various levels of aerobic fitness, on executive functioning, in which participants are classified as demonstrating a high or low level of aerobic fitness (Li et al., 2019; Themanson & Hillman, 2006).

5.5 Towards Neural Correlates of Stress and Exercise Effects on Executive Functioning

As the *Introduction* has discussed, the present scoping review was motivated by evidence that postulates acute experiences with psychosocial stress, as well as acute experiences of aerobic exercise, are associated with changes in PFC functioning. Because various areas of the PFC have

been proposed to be involved in executive functions (for a discussion, see Diamond, 2013), I was consequently interested in whether the effect of psychosocial stress on PFC function during tasks that predicate on flexibility, inhibition, and/or working memory may be modulated through acute participations in aerobic exercise. The results of my scoping review suggests that this may be the case. More precisely, modified variations of the TSST (Kirschbaum et al., 1993) were associated with increased BOLD in the ventromedial PFC (van Ast et al., 2016) as well as decreased BOLD within the dorsolateral (Luettgau et al., 2018) and dorsomedial (Van Ast et al., 2016) PFC during working memory tasks. For inhibition, the TSST (Kirschbaum et al., 1993) was associated with a greater BOLD contrast in regions of the frontal gyrus in participants who performed an inhibition task (Chang et al., 2020b).

In comparison, variations of cycling were associated with changes in the concentration of oxygen in the dorsolateral PFC in participants who performed inhibition tasks (Endo et al., 2013; Faulkner et al., 2016; Ochi et al., 2018b; Yanagisawa et al., 2010). When participants walked for approximately 20 min, walking was associated with decreased N2 amplitude among women who performed a modified Go/NoGo task in comparison to women who performed the task following seated rest of a comparable duration (Hwang et al., 2019). Finally, cycling was also associated to changes in BOLD contrast in the PFC in women who performed working memory tests (Li et al., 2014).

5.5.1 Stress and Exercise Effects on Inhibition

With women, regular aerobic exercise has been associated with an increase in oxygenated hemoglobin concentrations in the right inferior frontal gyrus while participants performed Stroop tasks (Dupuy et al., 2015). More precisely, Dupuy et al. (2015) observed that those who achieved a mean maximal oxygen reuptake value of 46.6 ± 7.0 ml/min/kg showed higher concentrations in

oxygenated hemoglobin in the right inferior frontal gyrus while performing incongruent trials for a modified Stroop task in comparison to the fNIRS findings observed among those who achieved an average maximum oxygen reuptake value of 36.4 ± 5.3 ml/min/kg during the graded maximal exercise test. At the behavioural levels, women who achieved a mean maximum oxygen reuptake value of 46.6 ± 7.0 ml/min/kg during the graded maximal exercise test exhibited quicker reaction times as well as a statistical trend towards greater response accuracy, during incongruent trials of the modified Stroop test in comparison to the response accuracy and response times observed for those who achieved a mean maximum oxygen reuptake value of 36.4 ± 5.3 ml/min/kg during the graded maximal exercise test (Dupuy et al., 2015).

As Table 1 indicated, the above literature complements the results that Endo et al. (2013), Faulkner et al. (2016), Ochi et al. (2018b), as well as Yanagisawa et al. (2010) have found. From a general level such studies provide evidence for the involvement of the dorsolateral (Endo et al., 2013; Hwang et al., 2019; Faulkner et al., 2016; Ochi et al., 2018b; Yanagisawa et al., 2010) and the ventrolateral (Dupuy et al., 2015) PFC, in the context of exercise-induced changes, in various inhibition tests. Moreover, the findings that Dupuy et al. (2015) found in women complement the findings reported by the above literature, in that women with greater aerobic fitness show greater oxygenation levels in the PFC, by comparison to women with lower aerobic fitness. However, as Endo et al. (2013), Faulkner et al. (2016) nor Yanagisawa et al. (2010) did not specify the fitness level of participants, the findings from these studies can only be interpreted within the context of the effects of acute aerobic exercise on assessments of inhibition.

Together, the above literature provides support for the view that different types of aerobic exercise are associated with quicker response time, as well as an increase in the concentrations of oxygenated hemoglobin, in the dorsolateral (Endo et al., 2013; Faulkner et al., 2016; Yanagisawa

et al., 2010), and ventrolateral (Dupuy et al., 2015) regions of the PFC. More precisely, Dupuy et al. (2015) provide support for the view that regular participations in aerobic exercise, as assessed with the mean maximal oxygen reuptake value attained during a graded maximal exercise test, is associated with better inhibition in comparison to lower levels of aerobic exercise. It is, however, important to keep in mind that Dupuy et al. (2015) only evaluated women. With the exception of Endo et al. (2013) in which 5 men, and 8 women, were evaluated, the other articles are restricted to a predominantly male-only sample. As Appendix **D** suggests, Faulkner et al. (2016) evaluated 17 men whereas Yanagisawa et al. (2010) evaluated 17 men and 3 women. Because of these, the position that different forms of aerobic exercise are associated with improved inhibition, appears premature as a small number of studies have provided evidence in support of it and these studies represent unequal proportions of men and women. As such, future research is necessary in order to provide further evidence for the view that aerobic exercise, such as cycling, is associated with improvements in response times as well as changes in the concentration of PFC oxygenation, by studies that evaluate exercise-related changes in inhibition. Variations of the Stroop test (Stroop, 1935) should be used to assess inhibition in this respect, as the incongruent condition of the task can theoretically evaluate subcomponents of inhibition. Since optimal performance during these trials demand the integration of selective attention, conflict monitoring, and interference control in a goal-directed manner (Diamond, 2013; Guiney & Machado, 2013; Scarpina & Tagini, 2017; Stroop, 1935) the Stroop paradigm provides an opportunity to assess the role of aerobic exercise on the inhibitory component of executive functioning.

Previous EEG research has demonstrated stressor-induced changes in regions of the PFC, when participants performed modified variations of the Go/NoGo test (Dierolf et al., 2017, 2018; Jiang & Rau, 2018). For instance Dierolf et al. (2018) as well as Jiang and Rau (2017) found that

increased P3 amplitude was observed, when participants needed to withhold from responding for the Go/NoGo task following the cessation of acute stress by comparison to what was observed in participants who performed NoGo trials, following the cessation of a control, non-stressful event. The above literature did not consistently report stress-induced changes in response accuracy, and stressor-induced changes with reaction time, during the NoGo trials (for an example, see Jiang & Rau, 2017). Because P3 amplitude is thought to reflect one's withdrawal of a prepotent response (Dierolf et al., 2017, 2018) the results suggest that acute stress modulates neuroelectrical activity in regions of the dorsolateral PFC, during variations of the Go/NoGo, even when response times as well as response accuracy may be unaffected by acute stress. Although these findings provide evidence for the involvement of the dorsolateral PFC in response inhibition following stress it is critical to consider methodological differences in the above literature in comparison with that of Chang et al. (2020b).

One commonality was that, Chang et al. (2020b), Dierolf et al. (2018), and Jiang and Rau (2017) employed the TSST (Kirschbaum et al.,1993) to produce acute psychosocial stress. At the same time, these studies differed with one another, with respect to the non-stressful situation that was used in each study. Participants in the study by Chang et al. (2020b) performed the TSST by themselves, in that the speech task as well as the arithmetic task was performed without negative social evaluation. By comparison, participants in the study by Dierolf et al. (2018) performed the TSST in front of a reaffirming committee in that the speech test as well as the arithmetic test was performed in front of figures of authority who provided positive feedback. For participants in the study by Jiang and Rau (2017) a non-stressful situation was created by instructing participants to read, and then perform a serial subtraction task. Jiang and Rau (2017) did not specify whether the control manipulation of stress was performed alone. Because the above literature differed by how

situations of eustress, or a situation the individual appraises to benefit his or her well-being (for a definition on eustress, see Mill et al., 2018), were applied to which the acute effect for TSST was compared, the stress-induced changes in response inhibition findings reported were associated to different stress manipulations. For this reason, the findings reported from the above literature are difficult to compare with one another without exercising cautious interpretation.

In addition, the above literature evaluated response inhibition by a different manner from one another. Chang et al. (2020b) used the stop-signal task, whereas Dierolf et al. (2018), as well as Jiang and Rau (2017), used modified variations of Go/NoGo. Previous literature has proposed that, although stop-signal tasks and Go/NoGo tasks involve regions of the PFC, including that of the frontal gyrus (Cai et al., 2014), different stages of inhibition are evaluated in each. With stop-signal tasks, the need to execute inhibition arises when a *stop* signal shortly follows the *go* signal (Chang et al., 2020b; Raud et al., 2020) in comparison with Go/NoGo tasks, in which the need to execute inhibition arises when the NoGo signal appears at the beginning of a given trial (Jiang & Rau, 2017; Raud et al., 2020). Because of this, successful inhibition in stop-signal tasks arises as a result of withholding an already initiated motor response but successful inhibition in Go/NoGo tasks arises as a result of preventing oneself from initiating a response. By this manner, although stop-signal tasks and Go/NoGo tasks commonly involve areas of the PFC (Cai et al., 2014), it is incorrect to infer that stop-signal, and Go/NoGo, tasks evaluate the same stages of inhibition. As Chang et al. (2020b) used a stop-signal task, while Dierolf et al. (2018) as well as Jiang and Rau (2017) used a Go/NoGo task, to evaluate inhibition, the stress-induced changes in inhibition that these studies reported, reflect investigations on inhibiting an already initiated motor response, as is the case in the *stop* trials for the stop-signal task, or investigations on inhibiting an anticipated but an unlikely already initiated motor response, as is the case in NoGo trials with the Go/NoGo

task. As such cautious interpretation should be exercised when comparing the results that Chang et al. (2020b) observed in relation with previous literature, such as the studies, by Jiang and Rau (2017) and Dierolf et al. (2018).

Moreover, it is important to keep in mind that Chang et al. (2020b) employed fMRI while previous literature has commonly employed EEG (Dierolf et al., 2017, 2018; Jiang & Rau, 2017) for the assessment of stress-induced changes in inhibition. Again, this limits the comparability of findings because fMRI provides different information about brain activity, in comparison to EEG (Bunce et al., 2006). EEG detects changes in the combined electrical activation from networks of neurons, over a particular period of time (Blinowska & Durka, 2006; Lotte et al., 2015; Michel & Murray, 2012; Müller-Putz et al., 2015) and fMRI theoretically distinguishes changes in oxygen-carrying cerebral blood flow (Bandettini, 2009; Detre, 2006; Specht, 2020; Sutton et al., 2009) in response to a particular event. Accordingly the finding that the TSST is associated with increased BOLD contrast in regions of the frontal gyrus (Chang et al., 2020b) complements the finding that the TSST is associated with an increase in P3 amplitude (Dierolf et al., 2018; Jiang & Rau, 2017) as well as changes in N2 amplitude (Dierolf et al., 2017), N2 latency (Jiang & Rau, 2017, as well as P3 latency (Jiang & Rau, 2017). For the reasons described previously, however, the results the above literature reported should be compared to one another with caution due to variability in 1.) stress manipulation; 2.) cognitive task; and 3.) neuroimaging instrumentation.

5.5.2 Stress and Exercise Effects on Working Memory

With respect to working memory, there is evidence to suggest the involvement of the left anterior cingulate cortex during working memory tasks, following an exercise intervention (Li et al., 2019). For instance, Li et al. (2019) reported that higher aerobic fitness was associated with a greater BOLD contrast for the left anterior cingulate cortex for women who performed *n*-back by

comparison to women of low aerobic fitness, following 20 min of moderate intensity cycling. As Table 1 suggests these findings complement those that Li et al. (2014) found by showing that the acute effects of various forms of aerobic exercise may be modulated by aerobic fitness. Although the study by Li et al. (2019) examined the interaction between acute and chronic aerobic exercise on working memory performance and is consequently beyond the scope of my review, the results from their study are worth mentioning in that aerobic exercise of a varying duration (acute versus chronic) may be associated with concentration changes in oxygenation in the PFC in women who completed assessments of working memory.

As Table 1 also suggests Li et al. (2014) reported that cycling was associated with similar response accuracy, during working memory tasks in women. Using an identical working memory paradigm as that of Li et al. (2014), Li et al. (2019) reported cycling was associated with reduced response accuracy, during working memory tasks in women. Because Li and co-workers selected identical working memory tests, participants may have been more or less motivated to accurately perform their working memory tasks. Within this line of reasoning, it is possible that some of the women in the study by Li et al. (2019) were more motivated to perform the tasks accurately, than others, and the group differences reported in response accuracy may consequently result from the influence of factors other than the aerobic fitness of participants, the exercise intervention, and/or the difficulty imposed by assessments of working memory.

This review also observed evidence for the involvement of the PFC in studies of stressor-induced changes for working memory. For instance, Luettgau et al. (2018), Qin et al. (2009), and Van Ast et al. (2016) each found stressor-induced decreases in BOLD contrast in the dorsolateral PFC, by participants who performed 2-back. This finding is in contrast with evidence from fMRI research using a modified cold pressor task to induce acute stress and evaluated working memory

using a modified variant of the Sternberg item recognition task (Sternberg, 1969). For instance, a study by Porcelli et al. (2008b) found an increased BOLD contrast within the dorsolateral PFC in participants, who performed a modified Sternberg item recognition task (Sternberg, 1969) amid a modified version of the cold pressor task in comparison to the BOLD contrast found for this PFC region when the item recognition test was performed amid either a no-water or room temperature water control situation. The discrepancy may be attributed to variation in study methodology. To illustrate, Luettgau et al. (2018) and Van Ast et al. (2016) used a modified TSST to induce stress in participants while Porcelli et al. (2008b) used a modified cold pressor task. In addition, Qin et al. (2009), Luettgau et al. (2018), and Van Ast et al. (2016) each used *n*-back, for the assessment of working memory, whereas Porcelli et al. (2008b) used item recognition.

In the original cold pressor test, the participant immerses his or her hand in cold water for a few minutes (Hines & Brown, 1936). Porcelli et al. (2008b) utilized a similar version of the test in which the participant immersed his or her hand in *cold water*, *room temperature water*, as well as *no water,* to induce differential states of acute stress. Although stressor-induced changes in the concentration of salivary cortisol were not evaluated by Porcelli et al. (2008b) a cold pressor task does not generally elevate salivary cortisol responsiveness with participants (for a discussion, see Schwabe et al., 2008). In addition Porcelli et al. (2008b) employed a cold pressor test that did not comprise any components for negative social evaluation, such as performing the task in front of a video camera (Schwabe et al., 2008) that, based on a meta-analysis of previous literature, appears to be the only variation of the cold pressor task that theoretically increases salivary cortisol levels as an indicator of psychosocial stress (Dickerson & Kemeny, 2004). For these reasons, the stress-induced increases for BOLD contrast within the dorsolateral PFC during an item recognition task were associated with different components of acute stress in comparison to those of the TSST, as

participants in the study by Porcelli et al. (2008b) did not perform a speech nor serial subtraction in front of an evaluating committee, as was the case for participants in the studies by Luettgau et al. (2018) and Van Ast et al. (2016).

Other than the methodological differences discussed above, the included literature on the effects of acute stress on working memory differed in other aspects of study methodology within the context of the broader literature. For instance, Porcelli et al. (2008b) utilized a modified item recognition task (Sternberg, 1969), while Luettgau et al. (2018), Qin et al. (2009) as well as Van Ast et al. (2016) utilized variations of *n*-back, to assess working memory. While these tasks may both involve the PFC in general (Cai et al., 2014) item recognition primarily involves the search component of working memory, whereas *n*-back primarily involves information maintenance as well as information retrieval (Unsworth & Engle, 2007). As such, discrepant findings, related to stressor-induced concentration changes in cerebral blood flow in the dorsolateral PFC should be interpreted within the context of methodological differences among the articles included for my review (Luettgau et al., 2018; Qin et al., 2009; Van Ast et al., 2016) in association with broader literature (Porcelli et al., 2008b).

5.5.3 Stress and Exercise Effects on Flexibility

Studies that tested the acute influence of aerobic exercise upon flexibility were excluded for violating at least one of my requirements for inclusion (see *Section 3.4*). In spite of this, it is worth discussing the current evidence, with respect to exercise-induced alterations on flexibility. For situations that require switching, between alternating task demands, acute periods of aerobic exercise has been associated with quicker response time, and alterations in the P3 component of event-related potentials, that suggest improved task awareness (Bae & Masaki, 2019). One EEG study has, for instance, reported faster response time, a trend towards greater response accuracy,

increased P3 amplitude and decreased P3 latency in participants who performed a switching test following 30 min of walking or running at 70% maximal heart rate, by comparison to that found in participants who performed these tasks following 30 min of seated rest (Bae & Masaki, 2019). These findings were proposed to occur, as a result of exercise-induced arousal, by a manner that enhanced task performance. More precisely, the exercise-induced improvements, with respect to response times, occurred because exercise resulted in arousal which in turn resulted in narrowed attention (Bae & Masaki, 2019). Since the P3 component of event-related potentials may reflect information processing, conflict monitoring as well as with action selection (Dierolf et al., 2017, 2018), the exercise intervention was interpreted to result in arousal that remained in participants during the switching task that followed, which benefitted performance speed while keeping task accuracy somewhat unaffected (Bae & Masaki, 2019).

Finally, it is worth discussing evidence of stress-induced changes on flexibility within the broader literature. There is evidence in this topic that emerged during my literature search but did not meet the requirements for inclusion in this review. In one example, Kalia et al. (2018b) found that improvements in perseveration, or the ability to learn and execute a new response in favor of a previously accurate, but now task-irrelevant response, were associated, with greater oxygenated hemoglobin concentration within the left dorsolateral PFC, for men who performed a variation of the Wisconsin Card Sorting Task (Heaton, 1993) following a socially evaluative cold pressor test in comparison to the findings observed before the cold pressor task began. In a classic Wisconsin Card Sorting Task (Heaton, 1993), the participant sorts cards using one of multiple possible rules and the participant learns which sorting rule is correct, based on limited feedback. As such, Kalia et al. (2018b) provided evidence for the involvement of the PFC during tasks that require flexible behaviour in the form of switching between multiple thought modalities and the role of a socially

evaluative variation of physical stress. Yet, this study was excluded, during study selection, since the stress manipulation combined psychosocial stress and physical stress and would have made it difficult to isolate the influence of physical discomfort from that of negative social evaluation, on flexibility. As such, future research is needed to provide evidence for the involvements of the left dorsolateral PFC in the context of stressor-induced improvements in perseveration by studies that utilize psychosocial stressors, such as variations of the TSST or MIST.

5.6 Implications of the Cortisol Stress Response on Inhibition and Working Memory

From the studies selected from the stress literature, it is worth noting findings of stressor-induced changes in the cortisol response, and whether these changes were associated with stress-induced changes in PFC function as well as executive functioning. Because this review included four studies from the stress literature, and because these studies varied by methodology, the data reported from these studies must be compared to one another with caution.

Of the four studies included from the stress literature, Luettgau et al. (2018) was the only study, in which participants were classified as cortisol responders, or cortisol non-responders. In particular, Luettgau et al. (2018) found that, of the 28 participants, approximately 80% showed a TSST-related increase in the cortisol response, defined as a 1.25 nmol/l cortisol increase relative to the cortisol levels reported prior to stress onset. Yet, although the TSST was associated with a decrease in oxygenated cerebral blood flow within the right dorsolateral PFC during 2-back, this was not associated with TSST-induced increases in the cortisol response. Here, it is important to note that Luettgau et al. (2018) did not perform these correlational analyses separately, for those classified as cortisol responders, and for those classified as cortisol non-responders. As previous research has demonstrated that cortisol responders may recruit PFC regions different from those recruited by cortisol non-responders during an acute psychosocial stressor (Dedovic et al., 2009;

Pruessner et al., 2008), the observation that the TSST-related increases in cortisol level were not associated with TSST-induced decreases in PFC oxygenation, as Luettgau et al. (2018) reported, may reflect how these analyses were performed.

As mentioned previously, the remaining included studies from the stress literature did not categorize participants as cortisol responders and non-responders (Chang et al., 2020b; Qin et al., 2009; Van Ast et al., 2016). Here, Chang et al. (2020b) reported that TSST-related increases with the cortisol response were not associated with the TSST-related increases in oxygenated cerebral blood flow in the bilateral medial/superior frontal gyrus during the stop-signal test. In the studies by Qin et al. (2009) and Van Ast et al. (2016) a higher cortisol response to the stressor induction method was at times associated with a deterioration in performance during *n*-back tasks. Although the stress group in the study by Van Ast et al. (2016) performed slower and committed more errors during the modified *n*-back task, in comparison to the control group, Van Ast et al. (2016) did not analyze whether TSST-related increases in cortisol responsiveness were associated with TSST-induced changes in PFC oxygenation.

By comparison, Qin et al. (2009) observed that those women who demonstrated a greater cortisol response to an emotional stressor performed slower during the *n*-back tasks as well. Qin et al. (2009) also observed women who demonstrated higher stressor-related increases in cortisol responsiveness also showed a greater oxygenation within the anterior cingulate cortex relative to women who showed comparatively lower stressor-related increases in cortisol release. Although Chang et al. (2020b) and Van Ast et al. (2016) used modifications of the TSST (Kirschbaum et al., 1993) to produce a momentary stressor in participants, Qin and co-workers used violent scenes from Irréversible by Gaspar Noé (2002) to produce an acute stressor in participants (Qin et al., 2009; for details, see Table 1).

To summarize, evidence from the included literature indicates that experiencing an acute stressor can be associated with improvements in inhibition (Chang et al., 2020b), yet decrements in working memory performances (Qin et al., 2009; Van Ast et al., 2016) and that these stressor-related changes in core executive functions involve alterations in prefrontal oxygenation (Chang et al., 2020b; Luettgau et al., 2018; Qin et al., 2009; Van Ast et al., 2016). Yet, as noted above, it is imperative to recognize methodological differences in stressor induction, the type of executive function assessed, how each executive function was examined, as well as the observation that, of the four selected studies, only one study classified participants as a cortisol responder or cortisol non-responder (Luettgau et al., 2018). As such, the view that acute stress may be associated with changes in core executive functions, which in part involves changes in prefrontal oxygenation, is premature and warrants further investigation. To that end, future research may wish to categorize participants as cortisol responders or cortisol non-responders and, within each group, perform the statistical analyses to ascertain whether stressor-related changes in executive functioning, as well as whether stressor-related changes in prefrontal oxygenation, may be explained, from individual differences in stressor-related changes in cortisol release. Here, future research may wish to refer to the articles by Dedovic et al. (2009), and Pruessner et al. (2008), as a starting point in terms of how the associations above can be statistically analyzed.

5.7 Recommendations for Future Research

This section provides recommendations for future research on PFC involvement in stress- and aerobic exercise-related changes in flexibility, inhibition, and working memory. Because the present review is based on evidence, from ten studies, recommendations reflect the methodology and findings reported from the selected studies within the context of available evidence from the broader literature. Nevertheless, these recommendations should be interpreted with caution. The

literature on the general involvement for aerobic exercise on stress-related changes in flexibility, inhibition, or working memory, as well as the involvement of the PFC in this respect, will likely evolve with time. As evidence in this topic evolves, recommendations for research practice may change from those reported here.

5.7.1 Recommended Interventions of Acute Psychosocial Stressors

To begin, future research may want to consider tasks that combine a cognitive task, such as mental arithmetic, with a speech task within a situation perceived as uncontrollable as well as socially threatening to the participants. Tasks that comprise all of these components are thought to reliably increase cortisol release from the HPA system (Dickerson & Kemeny, 2004). To that end, variations of the TSST (Kirschbaum et al., 1993) may be used to induce acute psychosocial stress in participants. Because observing PFC function during a speech task may be difficult (for one example see Rosenbaum et al., 2018), future research may want to consider variations of the MIST (Dedovic et al., 2005), as well as variations for a socially evaluative serial subtraction task (Wang et al., 2005) to produce acute psychosocial stress in participants. Variations of the MIST (Dedovic et al., 2005), as well as variations of a socially evaluative serial subtraction task (Wang et al., 2005), have been shown to activate the HPA axis within a neuroimaging environment, and may be consequently used to produce acute psychosocial stress in participants. For a list of tasks that activate the HPA axis, and may consequently influence PFC function, future research might want to refer to the meta-analysis by Dickerson and Kemeny (2004).

By comparison, the literature search performed in the present review retrieved studies, by which the acute stress induction method employed was inappropriate. For example, past research has employed a modified Stroop task to induce acute stress in participants (Gianaros et al., 2006) which, based on the available evidence on tasks that reliably activate the HPA axis (Dickerson &

Kemeny, 2004), is not designed to produce acute stress in participants. Rather, Stroop (1935) has designed this test to allow researchers to assess inhibition within a laboratory setting. Though the Stroop task might be subjectively stressful to perform, particularly when participants perform the incongruent condition of the test, the Stroop test has not been shown to reliably activate the HPA axis. In other cases, participants have reported that a modified Stroop test was positive for one to experience (Summers et al., 1999). To that end, future research should consider employing tasks other than variations of the Stroop task (Stroop, 1935) to induce acute stress. Future studies may also want to consider against the use of violent film to induce acute *psychosocial* stress. Here, it is important to recognize that viewing violence can be stressful, insofar as the experience results in an activation of the HPA system. Yet, such experience represents *emotional* stress rather than *psychosocial* stress due to the absence of negative social evaluation (Qin et al., 2009). This may still be used to induce acute stress in participants, as long as researchers are aware that this type of stress does not technically represent psychosocial stress.

5.7.2 Recommended Interventions of Acute Aerobic Exercise

Next, future research may want to consider using ergometer cycling or treadmill walking to induce an acute participation in aerobic exercise of moderate intensity in participants. The use of ergometer cycling (Endo et al., 2013; Li et al., 2014, 2019; Ochi et al., 2018a, 2018b; Rejeski et al., 1992; Wang et al., 2015; Yanagisawa et al., 2010) or treadmill walking or running (Bae & Masaki, 2019; Hwang et al., 2019; Lowe et al., 2017; Pontifex et al., 2008) appears to be used to induce acute aerobic exercise of moderate intensity. Moreover, the available evidence postulates that ergometer cycling is commonly used to assess exercise-related changes on inhibition (Endo et al., 2013; Faulkner et al., 2016b; Ochi et al., 2018a, 2018b; Yanagisawa et al., 2010), whereas treadmill walking or running is commonly used to assess exercise-induced changes in flexibility

(Bae & Masaki, 2019), inhibition (Hwang et al., 2019; Lowe et al., 2017), and working memory (Pontifex et al., 2008). In selecting the exercise intervention to utilize, to assess the influence of the intervention on the core executive functions, future research may wish to consider the above evidence. For instance, the available evidence has not used ergometer cycling to assess exercise-related changes in flexibility or working memory whereas treadmill exercise has been employed to assess exercise-related changes in these core executive functions, which are important for one to consider, in designing the exercise intervention to assess the effect of the intervention, on any of the core executive functions.

5.7.3 Recommended Assessments of Inhibition

To assess the involvement of the PFC during stress-induced changes in inhibition, future research may want to consider variations of the Go/NoGo task, variations of the stop-signal test, or variations of the Stroop (Stroop, 1935) task to assess inhibition. The current review is limited to one study, which assessed the involvement of the PFC in stress-induced changes in inhibition (Chang et al., 2020b). This study used a variation of the stop-signal test to assess inhibition. Yet, as discussed in the *Introduction*, the stop-signal task is not the only available test to evaluate this core executive function (Diamond, 2013). Previous research has used variations of the Go/NoGo task (Dierolf et al., 2017, 2018; Jiang & Rau, 2017) or variations of the Stroop test (Dupuy et al., 2015) to assess inhibition in participants depending on the components of inhibition under study. As the *Introduction* has discussed, variations of a Stroop task evaluate components of inhibition, which in part vary from the components of inhibition, that variations of Go/NoGo or stop-signal tests evaluate (Diamond, 2013). For these reasons, future research may want to carefully adopt a test that, based on evidence from previous reviews, is designed to evaluate the inhibition aspects

of interest for researchers. To that end, future research may wish to refer to Diamond (2013), for a list of well-established tasks that are designed to assess inhibition.

However, it is important to recognize that performance on inhibition tasks are difficult to isolate from the influences of other executive functions, such as flexibility and working memory (Diamond, 2013). For example, inhibiting a natural tendency in favor of a less natural response requires the participant to hold in his or her mind, which information to ignore, and at the same time reassure that he or she makes the appropriate response, when task demands change. For this reason, future research may want to modify the inhibition test selected, whether it is a variation of a Go/NoGo, stop-signal, or a Stroop task, to ensure that the inhibition features of interest are assessed by the test while, at the same time, minimizing the influence of the other executive functions, such as processing speed and working memory, on task performance. Here, future research may wish to refer to Diamond (2013) for reference.

To test the involvement of the PFC during aerobic exercise-related changes in inhibition, future studies may want to consider using variations of the Go/NoGo task, variations of the stop-signal task, or variations of the Stroop (Stroop, 1935) task. Here again, future research may want to adopt an inhibition task that is designed to assess the components of inhibition of interest. For instance, variations for the Stoop test (Stroop, 1935) have been employed to assess the influence of various types of aerobic exercise on inhibition (Dupuy et al., 2015; Endo et al., 2013; Ochi et al., 2018a, 2018b; Yanagisawa et al., 2010). Here, some authors employed a Stroop test marked by a congruent condition, as well as an incongruent condition (Endo et al., 2013; Faulkner et al., 2016), whereas other authors employed a Stroop test characterized by a congruent condition, an incongruent condition, as well as a neutral condition (Yanagisawa et al., 2010). Recently, a new condition has been applied in modifications of the Stroop task. Here, the participant responds to

the word itself and ignore the fact that the colour-word stimulus appears in ink that differs from what the word suggests ("red" shown in blue ink; Dupuy et al., 2015; Sibley et al., 2006).

As previously mentioned, it can be difficult to isolate the effect of inhibition, from those of other executive functions, such as processing speed, that are not considered as core executive functions (Diamond, 2013). In the above condition of the Stroop task, performance is compared in this "switching" condition in comparison to performances in the incongruent condition. Here, successful inhibition is assumed when faster response times and/or better accuracy are observed for the incongruent condition in comparison to the switching condition (Sibley et al., 2006). If a participant does not show a deterioration in his or her performance in this respect, such as cases when the above behavioral measures are comparable in the incongruent condition, with those in the switching condition, then exercise-related improvements during the Stroop test, is attributed to inhibition, as well as to other executive functions (Sibley et al., 2006). To that end, in cases a future study is interested in using the Stroop test to evaluate inhibition, researchers may want to develop a variation of the task that includes a neutral condition, an incongruent condition, and a switching condition. A congruent condition can be included as well. Yet, the available evidence suggests that comparing response times during the neutral condition, with the response times in the incongruent condition, yields a greater Stroop effect, than comparing response times during the congruent condition with the reaction times in the incongruent condition (Yanagisawa et al., 2010). For this reason, it is less imperative to include a congruent condition, than it is for future research to ensure that the Stroop task includes a neutral condition, an incongruent condition as well as a switching condition. For previous research, which employed a switching condition, to assess aerobic exercise-related changes with inhibition, future research may wish to refer to the

studies Dupuy et al. (2015) as well as Sibley et al. (2006) for reference in designing a variation of the Stroop task that includes a switching condition.

5.7.4 Recommended Assessments of Working Memory

To assess the involvement of the PFC during stress-related changes in working memory, future studies may wish to consider using variations of the *n*-back task, or variations of the item recognition test (Sternberg, 1969) to assess working memory. The current review is restricted to three studies, which assessed the involvement of the PFC in stressor-related changes in this core executive function using modifications of the *n*-back test (Luettgau et al., 2018; Qin et al., 2009; Van Ast et al., 2016). As discussed in the *Introduction*, the *n*-back task is designed to evaluate a participant's ability to maintain information, in his or her mind, usually over a duration of a few seconds and to recognize that information at a later point in time (Diamond, 2013). As such, the *n*-back task is recommended to assess stress-related changes in working memory, insofar as one is interested in evaluating the components of working memory that are associated with the short term maintenance, as well as recognizing the information held in mind. In comparison, the item recognition test (Sternberg, 1969) has been used in previous studies, which demonstrated stress-related changes in working memory (for examples, see Porcelli et al., 2008a, 2008b).

As discussed in the *Introduction*, the Sternberg item recognition task (Sternberg, 1969) is designed to assess components of working memory, which in part vary, from the components of working memory that the *n*-back task is designed to assess. Here, the Sternberg item recognition task (Sternberg, 1969) commonly requires a participant to hold multiple items in his or her mind and to recognize, at a later point in time, whether the target information is present by the current display. Because of this, the Sternberg item recognition task (Sternberg, 1969) is similar to an *n*-back task, in that both tasks require a participant to maintain as well as recognize information to

evaluate working memory. Yet, an additional requirement of the Sternberg item recognition test is the fact that a participant must search through a display of information, which may contain as many as 16 items, to ascertain whether the display included the target information held in his or her mind (Sternberg, 1969). To that end, future research may want to consider using a modified Sternberg item recognition task (Sternberg, 1969), in the event that researchers are interested in evaluating a participant's ability to maintain, search for, as well as recognize information.

The present review is limited to a single study, which assessed aerobic exercise-induced changes in working memory (Li et al., 2014). Here, Li et al. (2014) used a modified *n*-back task in which participants indicated whether the current stimulus was a specific letter (0-back), if the current stimulus was the same as that shown in the previous trial (1-back) or if the current letter was the same as that displayed two trials previously (2-back). Recently, Li et al. (2019) applied an *n*-back paradigm similar to that used by Li et al. (2014). Yet, recent research on how aerobic exercise is associated with acute alterations on PFC oxygenation during working memory tasks has used variations of the Sternberg item recognition test (Sternberg, 1969) rather than variants of an *n*-back paradigm (Porcelli et al., 2008b). Here, the task used to evaluate working memory should depend on the components for working memory, in which the experimenter is primarily interested in evaluating as discussed above. If future research selects an *n*-back test to evaluate working memory performance, researchers may wish to modify the test to comprise of a 0-, 2-, as well as a 3-back condition, or an *n*-back task with a 1-, 2-, as well as a 3-back condition, for the reasons discussed below.

Since previous fMRI research indicates that 0- and 1-back are associated with *less* PFC involvement in association to 2- and 3-back (Li et al., 2014, 2019; Luettgau et al., 2019; Qin et al., 2009), future research may wish to employ an *n*-back test with the above conditions, so the

demand imposed upon working memory will be qualified by PFC involvement. Here, trials by which low working memory load is needed (i.e., 0-, 1-back) should be associated with a lesser involvement of PFC regions in comparison to trials that impose greater demand upon working memory (i.e., 2-, 3-back), based on evidence from fMRI studies, in which the *n*-back task was employed to assess PFC involvement during working memory performance within the context of the acute influence of a psychosocial stressor (Luettgau et al., 2018), or aerobic exercise (Li et al., 2014, 2019), on this core executive function.

In the same manner, future studies may wish to consider *against* using 0-back as well as 1-back within the *n*-back task. The available evidence suggests that each of these conditions are associated with comparable involvement in the PFC (Li et al., 2014, 2019; Luettgau et al., 2018; Qin et al., 2009), so the use of one of these conditions is more important than the use of both, to induce a task marked by low working memory load in participants. The condition selected, be it 0- or 1-back, is recommended to be compared against performances during 2- as well as 3-back, based from evidence, that 2- and 3-back, are associated with the involvement of several areas of the PFC (Li et al., 2014; Luettgau et al., 2018; Qin et al., 2009; Van Ast et al., 2016). Because a variety of modified *n*-back tasks have been used, within the relevant literature, as these research topics become further investigated, it is imperative for researchers to adopt a well-established *n*-back test that, beyond the studies included in the current review, has been shown to induce both aerobic exercise- as well as psychosocial stressor-related changes within the PFC.

5.7.5 Recommended Assessments of Flexibility

The present review did not include studies that assessed the core executive function that is flexibility. This was, in large part, due to the observation that few research has examined this executive function in relation to how psychosocial stress or aerobic exercise may result in acute

alterations in PFC function and that, of the studies retrieved from the literature search, all of the studies met the requirements for exclusion (for details, see *Section 5.1* and *Section 5.2*). Yet, for researchers interested in examining this core executive function, the review by Diamond (2013) provides a list of tasks that have been used to assess flexibility. Future research can also refer to the review by Guiney and Machado (2013) for a list of tests to assess flexibility. Like inhibition and working memory, flexibility refers to various cognitive processes (Diamond, 2013). To that end, future research may wish to select the test that may best investigate the sub-components of flexibility that are of interest for researchers. For instance, although variations of the Wisconsin Card Sorting Task (Heaton, 1993) are traditionally used to test flexibility (Diamond, 2013), it is imperative to recognize how this test is presumed to examine flexible behaviour (for details, see the *Introduction*), and whether an alternative task should be used, depending on the components of flexibility under study.

5.7.6 Limitations of Recommendations

In light of the recommendations above, it is important for the reader to keep in mind that such recommendations were made based on studies demonstrating variability in the intervention applied to induce an acute psychosocial stressor (Chang et al., 2020b; Luettgau et al., 2018; Van Ast et al., 2016), the intervention employed to produce acute aerobic exercise (Endo et al., 2013; Faulkner et al., 2016; Hwang et al., 2019; Ochi et al., 2018b; Yanagisawa et al., 2010) as well as the task used to evaluate inhibition (Chang et al., 2020b; Endo et al., 2013; Faulkner et al., 2016; Hwang et al., 2019; Ochi et al., 2018b; Yanagisawa et al., 2010), and working memory (Li et al., 2014; Luettgau et al., 2018; Qin et al., 2009; Van Ast et al., 2016). The inconsistency in research methodology makes it challenging to compare the results of these studies to one another without

exercising caution. As such, it is important to recognize that these recommendations, as previous sections discussed, are based on limited empirical evidence, which varied in study methodology.

5.8 Methodological Limitations

While this scoping review addressed my research objectives I acknowledge such a review protocol has limitations. As Appendix **A** indicates, my database search was restricted to PubMed and PsycInfo. While the number of databases selected is in line with guidelines, from the scoping review literature (Arksey & O'Malley, 2005; Peters et al., 2005), it may have excluded published articles of potential relevance, to our research questions. As I have discussed under *Section 3.2*, I circumvented this problem from searching articles through additional sources. I made this choice prior to performing the literature search, and in accordance with the guidelines, from the scoping review literature (Arksey & O'Malley, 2005; Peters et al. 2015).

As I have discussed with *Section 3.5* my inclusionary criteria (for details, see *Section 3.4*) resulted in the inclusion of 4 studies from the psychosocial stress literature and 6 studies from the aerobic exercise literature. As a result, I summarized and synthesized results, through a relatively small number of studies. Appendix **E** exemplifies my reasons for excluding studies showing that, for the majority of articles retrieved through my literature search, a study was often excluded, for failing to meet multiple requirements for inclusion such as not assessing executive functioning in a *pre-post* manner, as well as excluding neuroimaging. Appendix **E** does not describe the reasons for excluding each of the 542 articles that were unqualified for inclusion, but is rather intended to show my reasons for excluding a proportion of these articles.

Related to my inclusionary criteria I acknowledge that I revisited these over the course of study selection. As I selected articles for inclusion, I observed that a handful of studies within the psychosocial stress literature did not measure salivary cortisol responses to stress. For this reason

and following the approval from my research team, I altered my requirement for a stress study to measure salivary cortisol responses with the requirement that for the study to be included, it must have used a stress manipulation, that has been shown to increase salivary cortisol responses. This implicates that, though I did develop these inclusionary criteria, prior to performing my literature search, I revisited these criteria, during my literature search. At the same time, evidence suggests that it is equally imperative to develop inclusion criteria at the outset, as it is to revisit the criteria during the review process, as researchers become familiar with the literature, being reviewed (for a discussion, see Badger et al., 2000).

For reasons which Whitley and Ball (2002) have recommended, I also acknowledged that my qualitative summary can be based from studies with a decreased statistical power. As Table 2 suggests, most of the selected studies did not specify whether the sample size reported was based on calculating the number of participants required to address the research question. Out of the 10 articles, Li et al. (2014) was the only study that indicated that the reported sample size was based on what was required to detect the desired effects with $P<.05$, and a statistical power of .8. Since none of the remaining studies specified the statistical power associated with their study sample, I speculate that for those with a sample size below 30 (Field, 2018), my research summary may be based from studies with a statistical power, below the conventional .80-.95 range (for review, see Whitley & Ball, 2002). As a result, my scoping review of this literature, must be interpreted with caution, as the research summary may not accurately reflect the acute influences of psychosocial stress and aerobic exercise on inhibition and working memory, by the population from which the study samples were recruited.

Finally, the included studies in the present review, primarily investigated stressor- as well as exercise-related changes in PFC function at the level of alterations in electrophysiology (EEG)

and oxygenated cerebral blood flow (fMRI, fNIRS). Yet, previous research has demonstrated the possibility, for the general involvement of brain-derived neurotrophic factor, a protein that seems abundant within the brain, in the acute effects of aerobic exercise on brain function (for a review, see Knaepen et al., 2010). For instance, 30 mins of cycling at a moderate intensity, defined as the participant's 60% maximal oxygen reuptake achieved during a graded maximal exercise test, has been shown to increase the concentration of serum brain-derived neurotrophic factor by men and women in comparison to the concentration levels observed pre-exercise (Gold et al., 2003). Here, because brain-derived neurotrophic factor is thought to regulate HPA axis activation (Knaepen et al., 2010), the acute effect of aerobic exercise, on executive functioning, a process which appears to involve the PFC (Endo et al., 2013; Faulkner et al., 2016; Ochi et al., 2018b), might reflect the interplay among several neuroendocrine systems, that are not limited to the HPA system. To that end, future research may wish to address the involvement of brain-derived neurotrophic factor in addition to the involvement of cortisol, within the context of the involvement of aerobic exercise in participants who perform executive function tasks under moderate psychosocial stress.

Table 2. **Findings of sample size calculations, effect size calculations, and *P*-values**.

Study	Study Characteristics				Effect sizes of Behavioural Outcomes			
	N	Statistical significance threshold	Sample size calculation	Desired effect size	Response accuracy	Interpretation	Response times	Interpretation
Chang et al. (2020b)	30	*P*<.05	Unreported	Unreported	Unreported	N/A	Unreported	N/A
Endo et al. (2013)	13	*P*<.05	Unreported	Unreported	Unreported	N/A	Unreported	N/A
Faulkner et al. (2016)	17	*P*<.05	Unreported	Unreported	Unreported	N/A	[d = .51,.69], [d = .36,.51]	moderate
Hwang et al. (2019)	30	*P*<.05	Unreported	Unreported	Unreported	N/A	Unreported	N/A
Li et al. (2014)	14	*P*<.05	Reported	g = 1.41	ηp^2 = .54	large	ηp^2 = .37	large
Luettgau et al. (2018)	34	*P*<.05	*P*<.005	Unreported	ηp^2 <.001	small	ηp^2 = .02	small
Ochi et al. (2018b)	15	*P*<.05	Unreported	Unreported	Unreported	N/A	Unreported	N/A
Qin et al. (2009)	29	*P*<.05	*P*<.001	Unreported	Unreported	N/A	r = .546	large
Van Ast et al. (2016)	21	*P*<.05	*P*<.005	Unreported	Unreported	N/A	Unreported	N/A
Yanagisawa et al. (2010)	20	*P*<.05	*P*<.05	Unreported	Unreported	N/A	Unreported	N/A

Note. *N* represents sample size; *P* represents the cut-off value applied for statistical significance; under statistical significance threshold, the left column represents the *P*-values used for response times and/or response accuracy during the cognitive test applied, and the right column represents the *P*-values applied for statistical significance during EEG, fMRI, or fNIRS analysis; g presents G*Power calculation; ηp^2 represents partial eta-squared; *d* represents Cohen's *d*; and *r* represents Pearson's correlation coefficient. Effect size interpretation is based on Cohen (1988) and Lakens (2013). In the study by Faulkner et al. (2016), [*d* = .51,.69] represents the effect size reported for the "colour" and "word" condition of the modified Stroop test, respectively, when their task was completed following upright cycling in comparison to seated rest; within this study, [*d* = .36,.51] represents the effect size reported for the "colour" and "word" condition of the task, respectively, when completed following supine cycling, by comparison to seated rest; within this study, all *d*'s represent effect sizes associated with response times during the Stroop task, keeping in mind that Faulkner et al. (2016) did not report response accuracy. In the study by Qin et al. (2009) *r* = .546 represents the effect size associated with the relationship between cortisol responses, prior to the onset of *n*-back, and the response times observed, during the task. For clarity, the effect sizes are summarized with regard to group differences (stress vs. control; exercise vs. control) in response times and/or response accuracy during the cognitive task applied, as appropriate.

5.9 Methodological Strengths

In the present paper, a crucial strength is that I reviewed a growing topic of the literature. To the best of my knowledge, the acute effects of psychosocial stress and/or aerobic exercise for flexibility, inhibition, and working memory, as assessed through diffusion tensor imaging, EEG, fMRI, fNIRS, MEG, PET, and single-cell recording studies, have not been reviewed to date. For this reason I believe that a major strength is reviewing 30 years of progress of this literature (see

Appendix **A**). In a similar manner, my inclusionary criteria represents a strength with my review methodology. As can be seen in *Section 3.4* and in Appendix **B**, I created a strict set of inclusion requirements. While a recent meta-analysis reviewed the literature on stress-induced changes for these components of executive functioning, the authors also excluded neuroimaging studies, that recorded PFC activity during assessments of executive functioning (Shields et al., 2016a).

5.10 Conclusion

In conclusion, this scoping review found evidence for the involvement of the PFC, during tasks that require inhibition and working memory in the aftermath of psychosocial stress or in the aftermath of aerobic exercise. Findings from the included literatures were summarized, yet future research is necessary to evaluate the quality of the findings reported from these studies. This may be achieved in the form of a full systematic review, in order to subject the included literature to a more conservative review process, with the guideline and principles from the Centre for Reviews and Dissemination (Centre for Reviews and Dissemination, 2009). However, because the present review is based on a limited number of studies further studies are recommended in these areas of the literature before a systematic review is performed in order to provide further evidence for the acute efficacy of aerobic exercise upon stress-related changes on executive functioning. With the prevalence of stress for Canadians (Statistics Canada, 2019), the availability of different types of aerobic exercise provides an opportunity to evaluate their ability to help individuals manage day-to-day stressors. The results of this review suggest the utility of EEG, fMRI as well as fNIRS for future research on the role of aerobic exercise on stress-related changes on executive functioning within the general population.

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APPENDIX A. Database Search Terms

DATABASE	SEARCH TERMS
PsycInfo	"psychological stress" OR "psychosocial stress" OR "stress" OR "Trier Social Stress Test" OR "cortisol" OR "hydrocortisone" OR "hypothalamic pituitary adrenal axis" OR "HPA axis"
	AND "executive function" OR "cognitive processes" OR "cognitive control" OR "set shifting" OR "task switching" OR "cognitive ability" OR "executive functioning" OR "flexibility" OR "cognitive flexibility" OR "inhibition" OR "response inh
	AND "prefrontal cortex" OR "frontal lobe" OR "Broca's Area" OR "dorsolateral prefrontal cortex" OR "medial prefrontal cortex" OR "orbitofrontal cortex"
	AND "neuroimaging" OR "action potentials" OR "near infrared spectroscopy" OR "encephalography" OR "electroencephalography" OR "magnetoencephalography" OR "magnetic resonance imaging" OR "tomography" OR "diffusion tensor im
PubMed	(((((("1990/01/01"[Date - Publication] : "2020/06/07"[Date - Publication])) AND ("Stress, Psychological"[Majr:NoExp] OR psychological stress OR psychological stressor))
	AND ("Executive Function"[Majr] OR executive functions OR executive control OR executive controls OR "inhibition, Psychological"[Mesh] OR "Memory, Short-Term"[Mesh] OR working memory OR working memories))
	AND ("Prefrontal Cortex"[Mesh:NoExp] OR dorsolateral prefrontal cortex OR prefrontal cortex, dorsolateral OR cortices, dorsolateral prefrontal OR dorsolateral prefrontal cortices OR prefrontal cortices, dorsolateral OR ventromedial prefrontal
	AND "Adult"[Majr] OR adults OR adult OR young adult)
PsycInfo	"aerobic exercise" OR "exercise" OR "physical fitness" OR "physical activity"
	AND "executive function" OR "cognitive processes" OR "cognitive control" OR "set shifting" OR "task switching" OR "cognitive ability" OR "executive functioning" OR "flexibility" OR "cognitive flexibility" OR "inhibition" OR "response inh
	AND "prefrontal cortex" OR "frontal lobe" OR "Broca's Area" OR "dorsolateral prefrontal cortex" OR "medial prefrontal cortex" OR "orbitofrontal cortex"
	AND "neuroimaging" OR "action potentials" OR "near infrared spectroscopy" OR "encephalography" OR "electroencephalography" OR "magnetoencephalography" OR "magnetic resonance imaging" OR "tomography" OR "diffusion tensor im
PubMed	((((("1990/01/01"[Date - Publication] : "2020/06/07"[Date - Publication])) AND ("Exercise"[Majr] OR physical activity OR physical exercise OR acute exercise OR aerobic exercise OR exercise training))
	AND ("Executive Function"[Majr] OR executive functions OR executive control OR executive controls OR "inhibition, Psychological"[Mesh] OR "Memory, Short-Term"[Mesh] OR working memory OR working memories))
	AND ("Prefrontal Cortex"[Mesh:NoExp] OR dorsolateral prefrontal cortex OR prefrontal cortex, dorsolateral OR cortices, dorsolateral prefrontal OR dorsolateral prefrontal cortices OR prefrontal cortices, dorsolateral OR ventromedial prefrontal
	AND ("Functional Neuroimaging"[Majr] OR neuroimaging, functional OR functional brain imaging OR brain imaging, functional OR "Magnetic Resonance Imaging"[Majr] OR imaging, magnetic resonance OR fMRI OR MRI, functional OR fi
	AND "Adult"[Majr] OR adults OR adult OR young adult)

R "response inhibition" OR "working memory" OR "short term memory"
fusion tensor imaging" OR "evoked potentials"
nedial prefrontal cortex OR cortex, ventromedial prefrontal OR cortices, ventromedial prefrontal OR prefrontal cortex, ventromedial OR prefrontal cortices, ventromedial OR ventromedial prefrontal cortices OR ventral medial prefrontal cortex))
R "response inhibition" OR "working memory" OR "short term memory"
fusion tensor imaging" OR "evoked potentials"
nedial prefrontal cortex OR cortex, ventromedial prefrontal OR cortices, ventromedial prefrontal OR prefrontal cortex, ventromedial OR prefrontal cortices, ventromedial OR ventromedial prefrontal cortices OR ventral medial prefrontal cortex))
functional OR functional MRI OR "Electroencephalography"[Majr:NoExp] OR EEG OR electroencephalogram OR electroencephalograms OR "Positron-Emission Tomography"[Majr:NoExp] OR positron emission tomography OR PET scan OR "Magnetoencephalography"[Majr:NoExp]))

FILTERS
January 1990 - June 2020; Scholarly Journals; English; Adulthood (18+); Animal, Human, Male, Transgender, Female; Journal Article; Empirical Study
January 1, 1990 - June 7, 2020; Journal Article; Humans, Other Animals; English; Male, Female; MEDLINE; Adult: 19-44 years
January 1990 - June 2020; Scholarly Journals; English; Adulthood (18+); Animal, Human, Male, Transgender, Female; Journal Article; Empirical Study
January 1, 1990 - June 7, 2020; Journal Article; Humans, Other Animals; English; Male, Female; MEDLINE; Adult: 19-44 years

APPENDIX B. Screening Form for Independent Reviewer

Research Questions

i. How can psychosocial stress affect flexibility, inhibitory control, and working memory, and is this associated with activation changes in the PFC as assessed through EEG, fMRI, fNIRS, DTI, MEG, PET, and single-cell recording studies?

ii. How can moderate aerobic exercise affect flexibility, inhibitory control, and working memory, and is it associated with activation changes within the PFC, as assessed through EEG, fMRI, fNIRS, DTI, MEG, PET, and single-cell recording studies?

iii. What methods have been used to manipulate psychosocial stress and aerobic exercise?

iv. What assessment tools have been administered to test flexibility, inhibitory control, as well as working memory?

Instructions

To ensure that an inter-rater agreement may be established towards the studies included, please read the abstract of each article (n=552). After reading the abstract, then determine if the article meets our inclusion criteria (see below). If it is not possible to ascertain whether it meets our inclusion criteria after reading its abstract, then read its full-text (introduction, methodology, results, discussion) to determine its eligibility. In other words, for each article, first determine if it satisfies our requirement for inclusion, by applying the appropriate criteria on its title/abstract (see below). If you cannot determine its eligibility from its title/abstract alone, the next step will be to retrieve its full-text. After retrieving its full-text, apply the appropriate criteria. Although I encourage you to read the entire article, I emphasize reading the method and results sections the most carefully. If an article seems eligible based on its title/abstract, the next step is identical as that above, where its full-text should be retrieved, read, and the appropriate criteria applied (see below) to confirm its eligibility for inclusion.

On a Word Document, please record each article considered eligible after reading its full-text. On this document, the following information should be recorded for each article: Its author name(s), publication year, title, journal title, journal volume, journal issue (if available), page #, and doi.

Inclusion Criteria – *Stress*

I. Healthy adults between 18 and 40 years of age. A study sample is considered healthy if the authors reported participants were in good mental and physical health;

II. If the article involves nonhuman participants, their sample should be nonhuman primates (rhesus monkeys, bonnet monkeys). Studies involving nonhuman subjects, which are not subserved within the primate family, are excluded (mice, rats);

III. At least 1 neuroimaging modality (DTI, EEG, fMRI, fNIRS, MEG, PET, cell recordings), and areas subserved within the PFC should be assessed by the modality(ies) (dorsolateral, dorsomedial, ventrolateral, ventromedial, and/or medial PFC);

IV. To ensure that an acute state of psychological stress was manipulated, if an article studied the effect(s) of stress on executive functioning, the stressor must meet the following:

   a. *If stress is a within-subjects factor*, stress must be manipulated within a laboratory setting. This criterion excludes studies that focused on chronic stress (examination stress; stress-related disorders, such as post-traumatic stress disorder). The control and experimental condition of stress manipulation must be separated by at least 24 h. This means that, if participants were exposed to both stressful and non-stressful situations, but both conditions were performed on the same day, then the article is ineligible;

b. *If stress is a between-subjects factor*, the stressor must again meet criterion (a), as described above, insofar as it should be manipulated in a laboratory setting, using a paradigm that has been previously established to activate the HPA axis (see d, e, and f);

c. The stressor must not exceed 1 h in duration, but it may last for less than an hour;

d. The stressor must involve both socio-evaluative threat (performing in front of an evaluative audience; perceiving one's performance is diagnostic of intelligence), and uncontrollability (not knowing how long the task will last and/or how 'hard' the task will be, in cases where one performs an arithmetic task). **If it does not include a combination of these elements**, it may still be included, provided it meets all other applicable criteria;

e. The stressor may not be physical. This criterion excludes those that manipulated stress using the cold pressor task. Even if socio-evaluative threat was embedded within the cold pressor task (socially evaluative cold pressor task), it would still be excluded as it combines psychological (socio-evaluative threat) and physical (discomfort associated with cold water immersion) stress;

f. The stressor may be emotion-focused rather than socially evaluative. If a study manipulated psychological stress using aversive film, which is emotionally but not socially evaluatively stressful it is included but only if it was verified to be distressing by inducing elevations in salivary cortisol. This may be verified by examining whether the article itself included salivary cortisol assessment or if such assessments were not reported, if the article cited another study, that did show that the same stressor resulted in salivary cortisol elevations;

g. *If stress is a within-subjects factor*, the core component(s) of executive function should be assessed following each of the control and experimental manipulation and the same cognitive assessment should be used;

h. *If stress is a between-subjects factor,* the core component(s) of executive function should be assessed, before and following stress manipulation;

i. A study is included even if it did not assess cortisol to verify that the participants experienced stress, as a result of the stress induction. The stress paradigm should, however, have been previously shown to increase salivary cortisol responses (i.e., while the study in question did not assess cortisol other studies that employed the same paradigm, and did assess cortisol, found such paradigm led to elevations in salivary cortisol responses following its onset);

Inclusion Criteria – *Exercise*

I. Healthy adults between 18 and 40 years of age. A study sample is considered healthy if the authors reported participants were in good mental and physical health;

II. At least 1 neuroimaging modality (DTI, EEG, fMRI, fNIRS, MEG, PET, cell recordings), and areas subserved within the PFC should be assessed by the modality(ies) (dorsolateral, dorsomedial, ventrolateral, ventromedial, medial PFC);

III. To ensure that an acute experience of moderate aerobic exercise was induced, the article must meet the following criteria:

   a. The exercise protocol does not exceed 1 h in duration. In cases where the protocol embedded a warm-up and cool-down period, the entire procedure should not be > 1 h;

b. *If exercise is a within-subjects factor*, the core components of executive function must be assessed following the exercise and control condition;
    i. The experimental (exercise) and control (rest) condition should also be conducted at separate sessions and inter-session interval should last for more than 24 h. This criterion thus allows an exercise session to be, for instance, separated from a rest session by several days;
c. *If exercise is a between-subjects factor*, core components of executive functioning must be assessed before and following the exercise (and control, if such study has included a control/rest period; it is considered for inclusion even if no control was implemented, provided it meets all other appropriate criteria);
d. A study is included even if it assessed executive functioning *during* exercise but it must have also assessed executive functioning using the same cognitive task, prior to the exercise protocol and following its cessation;
e. Exercise intensity should be moderate (40%-60% of heart rate reserve; 50%-75% of maximal heart rate; 50%-75% of maximal oxygen reuptake), as ascertained by the authors. **If other indicators of exercise intensity** were used, then refer either to the introduction and/or discussion to ascertain whether their exercise modality is moderate in intensity;

Key terms and further notes

I. Executive functioning refers to cognitive flexibility, inhibitory control, and working memory. We focus on these components of executive functioning. Please refer to the paper by Diamond (2013) for more information on what each component is and how different terms can be used to refer to each.
    a. Note that flexibility may be referred to as cognitive flexibility, flexible behaviour, set-shifting or task-switching; inhibitory control may be referred to as behavioural inhibition, cognitive inhibition, response inhibition, or inhibition; and, finally, the final term of working memory may be referred to as maintaining, manipulating as well as updating to-be-remembered information.
II. PFC = prefrontal cortex;
    a. DTI = diffusion tensor imaging;
    b. EEG = electroencephalography;
    c. fMRI = functional magnetic resonance imaging;
    d. fNIRS = functional near infrared spectroscopy;
    e. MEG = magnetoencephalography;
    f. PET = positron emission tomography;
III. If a study involves human participants, their study sample is presumably healthy, if the authors considered the participants to be in good mental and physical health;
IV. If a study compares a clinical population (i.e., those with Post-Traumatic Stress Disorder) with a healthy control group (i.e., those without the disorder in question, and matched for age, education, and sex), it may be considered for inclusion, provided the study meets all other requirements from the appropriate set of criteria;
V. If a study sample consists of different age groups, such as when the study involved adults classified as young (aged 18-40 years) and older (aged 65-80 years), it may be considered for inclusion, provided the study meets all other requirements from the appropriate set of criteria;

APPENDIX C. Comprehensive Summary of Stress Findings

Author name(s) and publication year	Sample size, sex (M, F), and age (M±SD, range)	Menstrual cycle phase and oral contraceptive use	Stress protocol and duration (min)	Control protocol and duration (min)
Cheng et al. (2020b)	15 males, 15 females (20.6 ± 2.0 years) Range: 18-25	Only included those who did not use oral contraception; Menstrual cycle phase was, however, not controlled for	Trier Social Stress Test ~15 min	Speech and arithmetic task alone ~15 min
Stress	p. 4	p. 4 and 10, respectively	p. 2	p. 2
Luettgau et al. (2018)	34 males (25.62 ± 5.16 years) Range: 18-41	Unapplicable	Trier Social Stress Test ~10 min	Read alone ~10 min
Stress	p. 26	p. 26	p. 26	p. 26
Qin et al. (2009)	29 females (stress: 21.0 ± 2.1; control: 20.0 ± 1.8 years) Range: 18-25	Only included those taking single-phase contraception; All females tested during the luteal phase of menstrual cycle, defined as the final 14 days, through self-report	Clips from the film Irreversible by Gaspar Noé ~90 min	Clips from the film Comment j'ai tué mon père by Anne Fontaine ~90 min
Stress	p. 26	p. 26	p. 26	p. 27
Van Ast et al. (2016)	11 males, 10 females (22.4 ± 4.2 years) Range unreported	Unclear whether oral contraceptive use was controlled; All females tested during the luteal phase of menstrual cycle, with the time window unreported, by self-report	Trier Social Stress Test ~15 min	Wrote a story about an imaginary positive experience ~15 min
Stress	p. 545	p. 545	p. 545	p. 545-46

Was the stress manipulation within- or between-subjects?	If stress manipulation was within-subjects, inter-session interval (days)	Imaging modality	PFC region(s) of interest	Were salivary cortisol responses assessed?
Within-subjects	≥ 30 days	fMRI	bilateral superior frontal gyrus bilateral middle frontal gyrus	Yes
p. 4	p. 4	p. 4-5	p. 6	p. 4
Within-subjects	7 days	fMRI	right dorsolateral PFC	Yes
p. 26	p. 26	p. 27-28	p. 28	p. 27
Between-subjects	Unapplicable	fMRI	dorsolateral PFC superior PFC inferior PFC medial PFC	Yes
p. 26	p. 26	p. 27	p. 27-28	p. 26
Between-subjects	Unapplicable	fMRI	anterior cingulate dorsolateral PFC dorsomedial PFC ventromedial PFC	Yes
p. 545	p. 545	p. 546-47	p. 549-51	p. 546

If applicable, time points of cortisol assessment relative to stress onset (min)	Executive function(s) of interest investigated	Test(s) administered and duration (min)	Interval (min) between when cognitive test was administered relative to stress cessation
0 (T1), +5 (T2), +15 (T3), +55 (T4), +75 (T5), +95 (T6)	Response inhibition	Stop-signal task (3 runs of ~12 min each) ~50 min	~28 (Run 1), ~48 (Run 2), ~68 (Run 3) min
p. 5	p. 1-2	p. 4-5	p. 5
-30 (T1), -2 (T2), +10 (T3), +15 (T4), +30 (T5), +45 (T6)	Working memory	n-back (0- and 2-back) ~10 min	~20 min
p. 27	p. 26-28	p. 28	p. 27
-75 (T1), -60 (T2), +15 (T3), +60 (T4), +90 (T5)	Working memory	n-back (0- and 2-back) ~15 min	~5 min
p. 26	p. 26-27	p. 26-27	p. 26
-65 (T1), -45 (T2), 0 (T3), +3 (T4), +13 (T5), +45 (T6), +83 (T7), +120 (T8)	Working memory	n-back (2- and 3-back) ~30 min	~20 min
p. 545	p. 546	p. 546	p. 545

Findings.	
Within the stress group, did salivary cortisol levels increase and, if so, at which timepoints?	Were there group differences in executive functioning following the cessation of treatment (stress, control)?
Salivary cortisol levels increased at T3, and continued to increase until the final sample. This corresponds to increased salivary cortisol levels 15 min following stress onset and that these elevations in salivary cortisol were maintained upto 95 min following stress onset.	There were no differences in response accuracy or latency during "Go" trials. Relative to the control condition, however, they found that participants inhibited responses during "Stop" trials faster, following the cessation of stress. Relative to when they performed the non-stressful variation of the Trier Social Stress Test, participants withheld their responses faster, when it was appropriate during the stop-signal task following an acute experience of psychosocial stress.
p. 6	p. 6-7
Salivary cortisol levels increased at T3 and T4, and decreased at subsequent timepoints. This corresponds to increased salivary cortisol levels 10 and 15 min following stress onset before decreasing 30 and 45 min following its onset.	Relative to the control condition, there were no differences in response accuracy or latency during the 0- and 2-back following the cessation of stress. These findings were based on the observations that, in relation to reading alone, participants committed similar errors and responded at a similar speed during the 0- and 2-back, following an acute experience of psychosocial stress.
p. 27	p. 29
Salivary cortisol levels increased at T3, and decreased thereafter. This corresponds to elevated salivary cortisol levels 15 min following stress onset before decreasing 60 and 90 min after its onset.	Relative to the control condition, there were no differences in response accuracy or latency during the 0- and 2-back following the cessation of stress. These findings were based on the observations that, relative to viewing non-arousing clips, participants committed similar errors and responded at a similar speed during the 0- and 2-back after viewing clips from a violent film.
p. 28	p. 28
Salivary cortisol levels increased until T5, and decreased thereafter. These correspond with an increase in salivary cortisol levels approximately 15 min following stress onset, and that these responses decreased over time up until the final sample taken approximately 2 h following the onset of stress.	Relative to their control condition, there were no differences in response accuracy during 2- and 3-back following psychosocial stress. These findings were based on the observations that, relative to writing about an imaginary positive social experience, the participants committed a similar proportion of errors among the 2- and 3-back following their modified Trier Social Stress Test. Relative to the control condition, 3-back performance was slower following psychosocial stress, as ascertained by significantly increased response times during 3-back performance following the Trier Social Stress Test relative to 3-back performance after story writing.
p. 548	p. 548

Were stress-induced changes in executive functioning associated with salivary cortisol responses?	Were there group differences in PFC activity during the executive function task following the cessation of treatment (stress, control)?
Unreported	Relative to the control condition, the superior and medial regions of the frontal gyrus revealed patterns of bilateral activity as participants were required to withhold their responses during the stop-signal task, following the cessation of stress. The superior and medial regions of the frontal gyrus also revealed increased connectivity to the caudate and putamen regions of the striatum during Stop trials, following the cessation of stress relative to stop-signal performance following the cessation of the control condition.
p. 6-9	p. 7-8
Within the stress condition, salivary cortisol responses were not associated with response accuracy or latency during 0- and 2-back performance following the cessation of psychosocial stress.	Relative to the control condition, the right dorsolateral PFC revealed patterns of deactivation, as participants performed the 2-back. They did not, however, observe differential patterns of activity in the right dorsolateral PFC as participants performanced 0-back following the cessation of stress, relative to 0-back performance following quiet reading.
p. 29	p. 29
Within the stress condition, higher salivary cortisol responses were associated with longer response latency, during the 0- and 2-back. Within this condition, participants who revealed elevated salivary cortisol responses, before the *n* -back began, performed the task more slowly, relative to those who showed comparatively lower salivary cortisol levels at the same sampling timepoint.	Relative to the control condition, the dorsolateral PFC showed patterns of bilateral deactivation as participants performed the 2-back after viewing violent movie clips. They did not, however, observe differential patterns of (de)activation in the dorsolateral PFC as participants performed the 0-back following the cessation of stress relative to viewing non-arousing film clips. Relative to the control condition, they also found patterns of activation within the anterior and orbitofrontal areas of the medial PFC as participants performed the *n* -back after the first bout of stress.
p. 28	p. 29
Within the stress condition, higher salivary cortisol responses were associated with generally better *n* -back performance. Within this condition, participants who revealed elevated salivary cortisol also performed the *n* -back better than those who showed comparatively lower salivary cortisol levels. It should be noted that this finding was reported within the context of overall working memory which was based on the accuracy and latency data obtained, as described on p. 546.	Relative to rest, the PFC revealed patterns of activation and deactivation in participants that experienced the psychosocial stressor. While the anterior cingulate cortex and the ventromedial PFC were active, the dorsolateral PFC showed patterns of deactivation, as participants performed the *n* -back following the cessation of stress. Within the stress condition deactivation of the dorsomedial PFC was associated with improvements in *n* -back performance following the cessation of stress relative to performance at rest. In the former and latter, rest refers to fMRI scans performed at the beginning of the experiment before participants underwent the stress or control treatment.

Were stress-induced changes in PFC activity associated with salivary cortisol responses?	Notes, if applicable
Stress-induced changes in PFC activation, as described in the preceding column, were not associated with changes in salivary cortisol responses.	
p. 7-9	
Stress-induced changes in PFC deactivation, as described in the preceding column, were not associated with changes in salivary cortisol responses.	
p. 30	
Stress-induced activation of the anterior and orbitofrontal regions of the medial PFC were associated with increased salivary cortisol responses, such that a positive association was observed between activation in the anterior and orbitofrontal cortices and salivary cortisol responses as participants performed the *n* -back following psychosocial stress.	
p. 29	
Stress-induced changes in PFC activation, as described in the preceding column, were not associated with changes in salivary cortisol responses.	
p. 548-50	

APPENDIX D. Comprehensive Summary of Exercise Findings

Author name(s) and publication year	Sample size, sex (M, F), and age (M±SD, range)	Exercise protocol and duration (min)	Exercise intensity	Control protocol and duration (min)
Ende et al. (2013)	5 males, 8 females (23.0 ± 1.0 years) Range unreported	Cycling for 15 min, followed by 1 min of cooling down	20, 40, and 60% of maximal voluntary exercise	Remaining seated for 15 min
Exercise	p. 288	p. 289	p. 289	p. 289
Faulkner et al. (2016)	17 men (24.6 ± 4.3 years) Range unreported	Cycling for 30 min	45-60% of maximal oxygen uptake	Remaining seated for 30 min
Exercise	p. 882	p. 883	p. 883	p. 883
Hwang et al. (2019)	30 females (mean age: 20.4 years) Range: 18-22	5 min of warm-up, followed by 20 min of walking on a treadmill, followed by 5 min of cool-down	70-75% of maximal heart rate	Remaining seated, duration unreported
Exercise	p. 35	p. 35	p. 38	p. 35
Li et al. (2014)	15 females (M and SD unreported) Range: 19-22	5 min of warm-up, followed by 20 min of cycling on a stationary ergometer, followed by 5 min of cool-down	60-70% of maximal heart rate	Remaining seated for 20 min
Exercise	p. 2	p. 3	p. 3	p. 3
Ochi et al. (2018b)	7 males, 8 females (20.7 ± 2.1 years) Range: 18-25	Cycling for 10 min, followed by 15 min of seated rest	50% maximal oxygen uptake	Remaining seated for 25 min
Exercise	p. 76	p. 76	p. 75	p. 76
Yanagisawa et al. (2010)	17 males, 3 females (21.5 ± 4.8 years) Range: 19-24	Cycling for 10 min, followed by 15 min of seated rest	50% maximal oxygen uptake	Remaining seated for 25 min
Exercise	p. 1703	p. 1704	p. 1709	p. 1704

Was the exercise manipulation within- or between-subjects?	If exercise manipulation was within-subjects, inter-session interval (days)	Imaging modality	PFC region(s) of interest	Were salivary cortisol responses assessed?
Within-subjects	≥ 1 day	fNIRS	bilateral dorsolateral PFC left dorsolateral PFC	No
p. 289	p. 289	p. 289	p. 289	
Within-subjects	2-3 (at least 2 days, but no more than 3 days)	fNIRS	bilateral dorsolateral PFC	No
p. 883	p. 883	p. 883	p. 883, 885	
Within-subjects	Unapplicable. The control protocol was defined as participants sitting as EEG recordings were obtained, and as they performed the first of 2 Go/NoGo tasks. This preceded the exercise session, after which the second Go/NoGo task was performed.	EEG	medial PFC	No
p. 35	p. 35	p. 36	p. 36, 40	
Within-subjects	7 days	fMRI	Brodmann Area (BA 4, BA 10, BA 17, BA 19, BA 32, BA 47)	No
p. 3	p. 3	p. 3	p. 3-4	

Within-subjects	≥ 1 day	fNIRS	bilateral ventrolateral PFC bilateral dorsolateral PFC bilateral frontopolar area	No
p. 77	p. 77	p. 77	p. 77-78	
Within-subjects	≥ 1 day	fNIRS	bilateral dorsolateral PFC left ventrolateral PFC left frontopolar area	No
p. 1703	p. 1704	p. 1704	p. 1706-8	

If applicable, time points of cortisol assessment relative to exercise onset (min)	Executive function(s) of interest investigated	Test(s) administered and duration (min)	Interval (min) between when cognitive test was administered relative to exercise cessation
Unapplicable	Response inhibition	Stroop Test (incongruent, congruent) 5 min for some, and 15 min for others.	5, 15, and 20 min.
	p. 288	p. 289, 296	p. 289
Unapplicable	Response inhibition	Stroop Test (incongruent, congruent) ~30 min	5 min
	p. 883	p. 883	p. 883
Unapplicable	Response inhibition	Emotion-focused Go/NoGo (sad, neutral) ~15 min	90 min
	p. 35-36	p. 35-36	p. 35
	p. 35-36	p. 35-36	p. 35
Unapplicable	Working memory	n -back (0-, 1-, and 2-back) ~10 min	15 min
	p. 2-3	p. 3	p. 3
Unapplicable	Response inhibition	Stroop Test (congruent, incongruent, neutral) ~7 min	15 min
	p. 77	p. 76-77	p. 77
Unapplicable	Response inhibition	Stroop Test (congruent, incongruent, neutral) ~8 min	15 min
	p. 1704	p. 1704	p. 1704

Findings. Within the exercise group, did salivary cortisol levels increase and, if so, at which timepoints?	Were there group differences in executive functioning following the cessation of treatment (exercise, control)?
Unapplicable	Relative to the control condition, no differences were observed for response accuracy as participants performed the Stroop Test 5, 15, and/or 20 min following the cessation of exercise at 20, 40 or 60% maximal voluntary intensity. In relation to the control condition, however, participants performed the Stroop Test more quickly, when performed 15 mins, following the cessation of cycling at 40 and 60% maximal voluntary intensity. When the task was performed 5 or 20 min following the end of exercise at 40 or 60% maximal voluntary intensity, participants performed the Stroop Test at a similar speed, relative to when it was done before the exercise session began.
	p. 290

Unapplicable	Relative to the control condition, group differences with response accuracy were not reported. Relative to the control condition, however, reduced response latency was observed, as participants performed the Stroop Test following the cessation of upright and recumbent exercise. When exercise-induced changes in response latency were compared between both exercise conditions relative to performance during the control condition, both exercise conditions showed similar reductions in response latency in the Stroop Test.
	p. 884
Unapplicable	Relative to the control condition, group differences in response latency were unreported. Relative to the control condition, they did not observe differences in response accuracy when participants were required to withhold from responding to sad, relative to neutral, faces following the cessation of exercise. These findings were based on the observations that relative to performing "NoGo" trials that involved sad faces while seated, participants committed a similar number of errors to these trials, following the cessation of exercise.
	p. 36 and 38, respectively

	p. 36 and 38, respectively
Unapplicable	Relative to the control condition, there were no differences in response accuracy or latency as participants performed the 0-, 1-, and 2-back, following the cessation of exercise. These findings were based on the observations that, relative to performing the three *n* -back conditions while seated, participants committed more errors and responded more slowly, as a result of increasing task difficulty, but not as a result of exercise participation. While more errors and slower responses were observed, during the 2-back, relative to the other two *n* -back conditions, these findings were maintained to be independent of the effect of exercise.
	p. 4
Unapplicable	Relative to the control condition, reductions in response accuracy were observed, following an acute participation of hypoxic exercise. These findings were based on the observation that, the differential score for response accuracy pre- and post-seated rest was greater than those observed pre- and post-hypoxic exercise. Relative to the control condition, an increase in reaction time was also observed, following an acute participation of hypoxic exercise. These findings were based on the observations that, the differential reaction time score pre- and post-seated rest was greater, than what they observed pre- and post-hypoxic exercise.
	p. 79-80
Unapplicable	Relative to the control condition, improvements in response accuracy were observed following an acute participation of aerobic exercise. These findings were based on the observations that, the differential response accuracy score pre- and post-seated rest was reduced, than what was observed pre- and post-aerobic exercise. Relative to the control condition, quicker response times were also observed following an acute participation of aerobic exercise. These findings were based on the observation that the differential reduction in response time was greater pre- and post-aerobic exercise, than that observed pre- and post- seated rest.
	p. 1705-6
Were exercise-induced changes in executive functioning associated with salivary cortisol responses?	Were there group differences in PFC activity during the executive function task following the cessation of treatment (exercise, control)?
Unapplicable	Relative to baseline levels, the PFC revealed changes in bilateral activation and deactivation during Stroop performance depending on the on the preceding exercise intensity. Relative to baseline levels, the PFC revealed a bilateral increase in oxy-hemoglobin levels, during the Stroop Test when performed 5 min following exercise at 40% maximal voluntary intensity. Relative to baseline levels, the PFC revealed a bilateral decrease in oxy-hemoglobin level during the Stroop test when performed 5 min following exercise at 60% maximal voluntary exercise. Relative to baseline levels, the PFC revealed similar changes in deoxy-hemoglobin levels during the Stroop Test, when done 5 min following exercise at 40 and 60% maximal voluntary intensity. Here, baseline refers to fNIRS recordings 5 min following exercise, before post-exercise assessments of inhibition were administered.
	p. 291-92
Unapplicable	Relative to the control condition, the PFC revealed an increase in oxygen saturation, as participants performed the Stroop Test, following the cessation of upright and recumbant exercise. This finding appears to mirror the observation that, relative performing the Stroop Test while seated, the PFC revealed an increase in oxy-hemoglobin levels during Stroop performance following the cessation of exercise.
	p. 884-85
Unapplicable	Relative to the control condition, the medial PFC revealed a decrease in N2 amplitude as participants were required to withhold a motor response to sad faces. While participants showed increased N2 amplitude in response to sad faces, the expression of which indicated no response should be made, while seated, N2 amplitude reduced as participants performed these trials, following the cessation of exercise.
	o. 37-38
	p. 37-38
Unapplicable	Relative to the control condition, the PFC revealed patterns of activation and deactivation as participants performed the 2-back following the cessation of exercise. BA 10, BA 17, and BA19 were active while the remaining BA regions of interest revealed reduced patterns of deactivation. They did not, however, observe differential patterns of activation in any of the regions of interest as participants performed 0- and 1-back following the cessation of exercise relative to 0- and 1-back performance following a 20 min period of seated rest.

Appendix E. Reasons for Study Exclusion

*Al'Absi, M., Hugdahl, K., & Lovallo, W. R. (2002). Adrenocortical stress responses and altered working memory performance. *Psychophysiology*, *39*, 95-99. https://doi.org/10.1111/1469-8986.3910095

Stress

I. 40 healthy male adults between 20 and 40 years of age;
II. **No neuroimaging modality used, although plasma cortisol was assessed**;
III. Stress was experimentally manipulated;
IV. Stressor was 48 min in total – 24 min per stressor;
V. Stressor involved socio-evaluative threat, as participants performed a subset of the stressor in front of 2 experimenters while being videotaped (public speech). It was, however, unclear whether the arithmetic and public speaking were viewed as being uncontrollable;
   a. Task stressfulness assessed using the State-Trait Anxiety Inventory as well as the Profile of Mood States. Relative to low cortisol responders, high cortisol responders showed worse negative mood, as assessed through the Profile of Mood States' anger, anxiety, confusion, depression and fatigue subscales. The perceived stressfulness of the arithmetic or public speaking task was not, however, reported, such that the stressors' stressfulness were unconfirmed, other than the observation that all participants showed greater plasma cortisol responses to the public speech task than the arithmetic task.
VI. Stressor was not physical (serial addition; public speaking);
VII. **Working memory, as assessed by a dichotic listening task, which was proposed to tap into the selective attention and temporary maintenance components of working memory, was not assessed before stress induction**;

*Alexander, J. K., Hillier, A., Smith, R. M., Tivarus, M. E., & Beversdorf, D. Q. (2007). Beta-adrenergic modulation of cognitive flexibility during stress. *Journal of Cognitive Neuroscience*, *19*(3), 468-78. https://doi.org/10.1162/jocn.2007.19.3.468

Stress

I. 8 healthy male, and 8 healthy female, adults aged 18 to 39 years (confirmed via email);
II. **No neuroimaging modality used**;
III. Stress was experimentally manipulated – modified Trier Social Stress Test, in which the job interview was for law school of graduate school in the stress condition;
IV. Stressor was about 15 min in total (5 min speech, 5 min arithmetic); However, cognitive testing was embedded within the stress procedure, so stress exposure was presumably > the 15 min duration proposed in the original Trier Social Stress Test protocol, although probably still within 1 h in duration;
V. Stressor involved socio-evaluative threat and uncontrollability, as the Trier Social Stress Test was used, which has been shown to lead to salivary cortisol elevations following its onset (Kirschbaum, Pirke, & Hellhammer, 1993);
   a. Task stressfulness was confirmed through increases in blood pressure, heart rate, and subjective responses, with subjective stress assessed via the Stress Appraisal Measure.
VI. Stressor was not physical (i.e., did not impose metabolic demands);
VII. Cognitive flexibility, as assessed by the Compound Remotes Associates Test (Bowden & Jung-Beeman, 2003) and an anagram task, was embedded within the Trier Social Stress Test. Cognitive testing began shortly after participants started the stressor, and cognitive testing continued at approximately 2-min intervals over the course of the stress test, such that **changes in cognitive flexibility were not assessed pre-post**.

*Banks, S. J., Eddy, K. T., Angstadt, M., Nathan, P. J., & Luan Phan, K. (2007). Amygdala-frontal connectivity during emotion regulation. *Social Cognitive and Affective Neuroscience*, *2*, 303-12. https://doi.org/10.1093/scan/nsm029

Stress

I. 8 healthy female, and 6 healthy male, adults between 22 and 38 years of age;
II. fMRI used – regions of interest: amygdala, ACC, DLPFC, DMPFC, VLPFC, VMPFC, interior parietal cortex;
III. Experimental manipulation was intended to lead to negative affect, as participants viewed aversive images (i.e., dead bodies) and were asked to either maintain how they felt or re-appraise how they felt. While aversive images have been used to induce an acute state of psychological stress (Qin et al., 2009, 2012); **did not aim to examine stress but, rather, emotion regulation in healthy adults**;
   a. Aversive images, relative to neutral images, led to negative affect, as assessed via a 5-point Likert scale.
IV. **Stressor did not involve socio-evaluative threat**, as the participants were not instructed to view themselves as witnessing the event, but it may have been uncontrollable, as participants may not have known how long the task would last;
V. **No cognitive assessment.**

*Basso, J. C., Shang, A., Elman, M., Karmouta, R., & Suzuki, W. A. (2015). Acute exercise improves prefrontal cortex but not hippocampal function in healthy adults. *Journal of the International Neuropsychological Society*, *21*(10), 791-801. https://doi.org/10.1017/S135561771500106X

Exercise

I. 51 healthy female, and 34 healthy male, adults between 18 and 35 years of age;
II. **No neuroimaging modality used**;
III. Response inhibition, as assessed by the Stroop Colour-Word Test, was assessed pre- and post-exercise or control;
IV. **Exercise intensity was vigorous**, as the exercise group was instructed to cycle at 85% of their maximal heart rate for 1 h (5 min warm-up, 50 min cycling, 5 min cool-down);

Bediz, C. S., Oniz, A., Guducu, C., Ural Demirci, E., Ogut, H., Gunay, E., Cetinkaya, C., & Ozgoren, M. (2016). Acute supramaximal exercise increases the brain oxygenation in relation to cognitive workload. *Frontiers in Human Neuroscience*, *10*, 1–11. https://doi.org/10.3389/fnhum.2016.00174

Exercise

I. 35 healthy male adults between 18 and 23 years of age;
II. fNIRS used to measure oxygenation, deoxygenation, and total blood volume in the PFC;

III. Working memory, as assessed by the n-back task, was assessed pre- and post-exercise;
IV. Exercise protocol used was the **Wingate Anerobic Test**, which assessed the individual's physiological responses to an acute fitness test of high-intensity;
   a. Exercise protocol was approximately 10 min in duration (5 min warm-up, 30 s Wingate test, 5 min cool-down);

Berchicci, M., Lucci, G., Perri, R. L., Spinelli, D., & Di Russo, F. (2014). Benefits of physical exercise on basic visuo-motor functions across age. *Frontiers in Aging Neuroscience*, *6*. https://doi.org/10.3389/fnagi.2014.00048

Exercise

I. 84 healthy participants (10 females, 20 males aged 19-35; 12 females, 20 males aged 40-63; 14 females, 8 males aged 65-86);
II. EEG used to assess event-related potentials associated with prefrontal, motor, and visual cortical areas;
III. **Processing speed, as assessed by a Simple Response Task, assessed once**;
IV. **No exercise protocol**. Rather, participants were classified as being physically active or inactive using a self-report questionnaire;

*Buchanan, T. W., Tranel, D., & Adolphs, R. (2006). Impaired memory retrieval correlates with individual differences in cortisol response but not autonomic response. *Learning and Memory*, *13*, 382-87. https://doi.org/10.1101/lm.206306

Stress

I. 16 healthy male, and 16 healthy female, adults between 18 and 21 years of age;
II. **No neuroimaging modality used, although salivary cortisol assessments performed**;
III. **Stressor was physical**, as the cold pressor test was used in a subset of participants;
IV. Stressor **excluded socio-evaluative threat and uncontrollability**. The paradigm was not socially evaluative nor uncontrollable, as participants were unobserved by an evaluative audience and were told how long to immerse their hand in cold water, respectively;
V. **Although cognitive assessment was administered pre-post, declarative memory was assessed**.

Buckert, M., Kudielka, B. M., Reuter, M., & Fiebach, C. J. (2012). The COMT Val158Met polymorphism modulates working memory performance under acute stress. *Psychoneuroendocrinology*, *37*(11), 1810–21. https://doi.org/10.1016/j.psyneuen.2012.03.014

Stress

I. 14 healthy female, and 19 healthy male, participants. Age range unreported – emailed;
II. **No neuroimaging modality used, although salivary cortisol assessments obtained**;
III. Stressor was psychosocial, as the Trier Social Stress Test – Group was used. Although this is a relatively new paradigm, it induced an acute state of stress, as evidenced with elevated salivary cortisol responses following its onset, in combination with worsened mood, as assessed by a German Mood Questionnaire;
IV. Stressor involved both socio-evaluative threat and uncontrollability;
V. Working memory, as assessed by 1-, 2-, and 3-back levels of the verbal n-back task, was assessed following the experimental and control condition of the Trier Social Stress Test – Group, noting that stress served as a within-subjects factor;

*Chang, Y. K., Tsai, C. L., Hung, T. M., So, E. C., Chen, F. T., & Etnier, J. L. (2011). Effects of acute exercise on executive function: A study with a Tower of London task. *Journal of Sport and Exercise Psychology*, *33*(6), 847-65. https://doi.org/10.1123/jsep.33.6.847

Exercise

I. 29 healthy female, and 13 healthy male, adults. Awaiting email response to confirm age range;
II. **No neuroimaging modality used**;
III. Exercise protocol did not exceed 1 h in duration;
IV. The Tower of London Task, which has been proposed to assess flexibility, inhibition, and working memory, was assessed before and following exercise;
V. Exercise intensity was moderate, as participants with high, moderate, and low physical activity, as assessed by the International Physical Activity Questionnaire, were asked to maintain 70%, 60%, and 50% of their heart rate reserve during exercise, respectively;

**Chang, J., Hu, J., Li, C. S. R., & Yu, R. (2020b). Neural correlates of enhanced response inhibition in the aftermath of stress. *NeuroImage*, *204*(116212). https://doi.org/10.1016/j.neuroimage.2019.116212

Stress

I. 15 healthy female, and 15 healthy male, adults between 18 and 25 years of age;
II. fMRI used, as well as salivary cortisol assessments;
   a. Regions of interest included regions within the PFC (superior frontal gyrus, medial frontal gyrus) in association with their connectivity to the striatum;
III. Stressor was psychosocial, as the Trier Social Stress Test was used;
IV. Stressor involved both socio-evaluative threat and uncontrollability;
V. Response inhibition, as assessed by the stop-signal task, was assessed following stress as well as its respective control condition. Of note, stress served as a within-subjects factor, its experimental and control condition was performed at separate sessions, session order was counterbalanced across participants, and inter-session interval was over 24 h (~30 days).

*Coles, K., & Tomporowski, P. D. (2008). Effects of acute exercise on executive processing, short-term and long-term memory. *Journal of Sports Sciences*, *26*(3), 333-44. https://doi.org/10.1080/02640410701591417

Exercise

I. 18 healthy adults between 18 and 25 years of age – Confirmed by email correspondence;
II. **No neuroimaging modality used**;
III. Exercise protocol did not exceed 1 h in duration;
  a. The experimental manipulations of exercise (cycling, sitting, TV watching) were separated by approximately 7 days;
  b. The intensity of the exercise intervention was moderate, as it required participants to exert 60% of their peak oxygen consumption, which was determined during the graded maximal test during the initial session;
IV. The maintenance component of working memory, as assessed by a modified Brown-Peterson Test and a free-recall task, as well as the task-switching component of both cognitive flexibility and inhibitory control, as assessed by a visual switch task, were assessed pre- and post-intervention;

Colzato, L. S., Kool, W., & Hommel, B. (2008). Stress modulation of visuomotor binding. *Neuropsychologia*, *46*(5), 1542–48. https://doi.org/10.1016/j.neuropsychologia.2008.01.006

Stress

I. 8 healthy female, and 9 healthy male, adults between 18 and 27 years of age;
II. **No neuroimaging modality used, although salivary cortisol was assessed**;
III. Stressor was experimentally manipulated, but it was a **physical stressor**;
  a. The cold pressor test was used so, while an acute state of stress was induced and confirmed by elevations in salivary cortisol responses following its onset, it was devoid of socio-evaluative threat and uncontrollability;
  b. Inter-session interval was 3-7 days, and stress served a within-subjects factor;
IV. Visual and motor function, as assessed by a simple response task, was assessed. None of the core components of executive functioning were assessed in the study as these aspects were not of interest. In other words, **executive functioning was unassessed**.

*Cornelisse, S., van Stegeren, A. H., & Joëls, M. (2011). Implications of psychosocial stress on memory formation in a typical male versus female student sample. *Psychoneuroendocrinology*, *36*(4), 569-78. https://doi.org/10.1016/j.psyneuen.2010.09.002

Stress

I. 54 healthy female, and 23 healthy male, between 18 and 25 years of age;
II. **No neuroimaging modality used, although salivary cortisol was assessed**;
III. Stressor was experimentally manipulated;
  a. The Trier Social Stress Test was used, and successful induction of an acute state of stress was confirmed through increased in momentary negative mood, as well as by salivary cortisol and salivary alpha-amylase elevations, following its onset;
IV. Working memory, as assessed by 0-, 2-, and 3-back conditions of the n-back task, was assessed following the treatment (stress, control). This was assessed following a test of long-term memory as assessed by participants rating their arousal to pictures of various emotional content (negative, neutral);
  a. **Working memory was only assessed following the cessation of stress/control**;

*Cousijn, H., Rijpkema, M., Qin, S., van Wingen, G. A., & Fernández, G. (2012). Phasic deactivation of the medial temporal lobe enables working memory processing under stress. *NeuroImage*, *59*(2), 1161-67. https://doi.org/10.1016/j.neuroimage.2011.09.027

Stress

I. 41 healthy men between 18 and 35 years of age;
II. BOLD and perfusion fMRI used;
  a. Regions of interest included the dorsolateral prefrontal cortex;
  b. Salivary cortisol and alpha-amylase were assessed throughout the experiment;
III. Stressor was experimentally manipulated;
  a. While stress was induced using clips from an aversive film ("Irreversible"), a successful stress induction was confirmed through elevations in salivary cortisol, alpha-amylase, and negative affect (as measured by the Positive Affect Negative Affect Scale);
  b. Stress excluded socio-evaluative threat, but included uncontrollability presumably as participants were instructed to imagine themselves 'witnessing' the violence in the film;
  c. **The control and experimental condition of stress was performed on the same day**, as authors proposed that the conditions were separated by approximately 20 min;
IV. Working memory, as assessed by 0- and 2-back conditions of the n-back task, was tested within the experimental and control condition of stress. In other words, it was embedded within the stressful condition;

*Dedovic, K., Renwick, R., Mahani, N. K., Engert, V., Lupien, S. J., & Pruessner, J. C. (2005). The Montreal Imaging Stress Task: Using functional imaging to investigate the effects of perceiving and processing psychosocial stress in the human brain. *Journal of Psychiatry and Neuroscience*, *30*(5), 319-25. PMID: 16151536.

Stress

I. 1 healthy female, and 9 healthy male, adults between 21 and 30 years of age (Study 1); 10 healthy male adults between 20 and 25 years of age (Study 2); 22 healthy male adults between 20 and 24 years of age (Study 3);
II. PET and fMRI used, with salivary cortisol assessed in each study;
III. Stress was experimentally manipulated via Montreal Imaging Stress Task;
  a. Involved socio-evaluative threat and uncontrollability, and successful induction of stress confirmed through elevations in salivary cortisol levels following its onset;

IV. **Executive functioning unassessed in neither Study 1, 2, or 3**;

*Dedovic, K., Rexroth, M., Wolff, E., Duchesne, A., Scherling, C., Beaudry, T., Lue, S. D., Lord, C., Engert, V., & Pruessner, J. C. (2009). Neural correlates of processing stressful information: An event-related fMRI study. *Brain Research*, *1293*, 49-60. https://doi.org/10.1016/j.brainres.2009.06.044

Stress

I. 28 healthy male adults, with a mean age of 23 years and an SD of 4.48 years;
II. fMRI used, with salivary cortisol assessed and PFC among their regions of interest;
III. Stress was experimentally manipulated via modified Montreal Imaging Stress Task;
  a. Involved socio-evaluative threat and uncontrollability, and successful stress induction confirmed in a subset of participants showing significant salivary cortisol responses;
  b. **Conditions of stress (control, experimental) conducted in the same day**;
IV. Executive functioning unassessed;

*Del Giorno, J. M., Hall, E. E., O'Leary, K. C., Bixby, W. R., & Miller, P. C. (2010). Cognitive function during acute exercise: A test of the transient hypofrontality theory. *Journal of Sport and Exercise Psychology*, *32*(3), 312-23. https://doi.org/10.1123/jsep.32.3.312

Exercise

I. 13 healthy female, and 17 healthy male, adults aged 20.2 ± 1.1 years;
II. **No neuroimaging modality used**;
III. Exercise intervention was experimentally manipulated, and was a within-subjects factor;
  a. Protocol was acute (within 1 h duration), moderately intense (at VT or 75% VT);
  b. Inter-session interval of VT/75% VT occurred 5.7 ± 6.2 days of one another;
IV. Cognitive flexibility, as assessed by a variant of the Wisconsin Card Sorting Test, was assessed before, during, and following the exercise protocol (immediately, and 20 min-post);

*Dierolf, A. M., Fechtner, J., Böhnke, R., Wolf, O. T., & Naumann, E. (2017). Influence of acute stress on response inhibition in healthy men: An ERP study. *Psychophysiology*, *54*(5), 684-95. https://doi.org/10.1111/psyp.12826

Stress

I. 41 healthy male adults between 19 and 30 years of age;
II. EEG used, with areas of the frontal cortex among the regions of interest (i.e., anterior cingulate cortex, inferior frontal gyrus);
III. Stress was experimentally manipulated, but the **socially evaluative cold pressor test** (or respective control condition) was used to induce an acute state of stress. While its ability to induce an acute state of stress was confirmed in a subset of participants as determined by salivary cortisol elevations following its onset the stressor itself combined physical & psychological stress.
IV. Response inhibition, as assessed by the Go/NoGo task, was assessed before and after the stress manipulation (stress, control);

*Dierolf, A. M., Schoofs, D., Hessas, E. M., Falkenstein, M., Otto, T., Paul, M., Suchan, B., & Wolf, O. T. (2018). Good to be stressed? Improved response inhibition and error processing after acute stress in young and older men. *Neuropsychologia*, *119*, 434-47. https://doi.org/10.1016/j.neuropsychologia.2018.08.020

Stress

I. 30 healthy adults, aged 24.28 ± 3.56 years. Of note, older healthy adults were included in this study who were aged 67.26 ± 4.50 years. The whole sample was aged 19 to 75 years;
II. EEG used, with areas of the frontal cortex among the regions of interest;
  a. Salivary cortisol assessments were also included;
III. Stress was experimentally manipulated via the Trier Social Stress Test;
  a. Stress involved socio-evaluative threat and uncontrollability, and successful stress induction was qualified by salivary cortisol elevations in the stress group, relative to the control group;
IV. **Response inhibition, as assessed by the Go/NoGo task, was only assessed following the treatment** (stress, control), noting that stress was a within-subjects variable. While participants performed practice trials on the Go/NoGo before treatment, pre-stress data were not obtained.

Dietl, T., Vogl, L., & Dirlich, G. (2004). Auditory information processing is altered in novelty stress conditions: First session effects in auditory-evoked potentials. *International Journal of Neuroscience*, *114*(1), 131–42. https://doi.org/10.1080/00207450490249437

Stress

I. 10 (Study 1) and 12 (Study 2) healthy male adults between 20 and 35 years of age;
II. EEG used and positioned over the fronto-parietal areas. Plasma cortisol also assessed;
III. Stress was experimentally manipulated in the form of exposing participants to a novel situation, using an auditory variant of the oddball paradigm. It included neither socio-evaluative threat nor uncontrollability (in relation to stress) as participants only listened to the sounds presented;
  a. Stress induction was, however, qualified by higher plasma cortisol responses in the first session relative to subsequent sessions noting that sessions were similar with one another, in relation to what was expected from participants;
IV. **Neither of the core components of executive functioning were assessed**, as the study goal was to primarily examine, whether a novel situation may be stressful, and whether such stressfulness subsides, over repeated exposure, as assessed via changes in plasma cortisol;

*Domes, G., Heinrichs, M., Reichwald, U., & Hautzinger, M. (2002). Hypothalamic-pituitary-adrenal axis reactivity to psychological stress and memory in middle-aged women: High responders exhibit enhanced declarative memory performance. *Psychoneuroendocrinology*, *27*(7), 843-54. https://doi.org/10.1016/S0306-4530(01)00085-3

Stress

I. **32 healthy females between 32 and 68 years**;
II. **No neuroimaging modality used, although salivary cortisol was assessed**;
III. Stress was experimentally manipulated, in the form of the Trier Social Stress;
   a. The stressor consisted of socio-evaluative threat and uncontrollability;
   b. Successful stress induction confirmed by salivary cortisol elevations in a subset of participants following the onset of the Trier Social Stress Test;
IV. **Neither the core components of executive functioning assessed**. Declarative memory, as assessed by a free recall, following a delay, was assessed following exposure to either the Trier Social Stress Test or its respective control condition;

*Eisenberger, N. I., Lieberman, M. D., & Williams, K. D. (2003). Does rejection hurt? An fMRI study of social exclusion. *Science*, *302*, 290. https://doi.org/10.1126/science.1089134

Neither stress/exercise

I. 9 female, and 4 male, participants. Age range unreported, and emailed for confirmation;
II. fMRI used, with regions of the PFC investigated;
III. **Experimental manipulation was social exclusion**;
   a. While the paradigm may have been socially evaluative and/or uncontrollable, as participants experienced social exclusion the paradigm was probably unintended to lead to psychosocial stress. Rather it is commonly intended to induce an acute state of social exclusion (Cyberball) rather than stress per se;
IV. **Neither the core components of executive functioning assessed**;

*Eisenberger, N. I., Taylor, S. E., Gable, S. L., Hilmert, C. J., & Lieberman, M. D. (2007). Neural pathways link social support to attenuated neuroendocrine stress responses. *NeuroImage*, *35*(4), 1601-12. https://doi.org/10.1016/j.neuroimage.2007.01.038

Stress

I. 19 healthy female, and 13 healthy male, adults between 18 and 36 years;
II. fMRI used, with regions of the PFC and salivary cortisol investigated;
III. Stress was experimentally manipulated via the Trier Social Stress Test;
   a. Stressor involved socio-evaluative threat and uncontrollability;
   b. Successful stress induction qualified by salivary cortisol elevations following stress onset relative to baseline;
IV. **Neither of the core components of executive functioning were assessed**;

*Erickson, K. I., Colcombe, S. J., Wadhwa, R., Bherer, L., Peterson, M. S., Scalf, P. E., Kim, J. S., Alvarado, M., & Kramer, A. F. (2007). Training-induced functional activation changes in dual-task processing: An fMRI study. *Cerebral Cortex*, *17*(1), 192-204. https://doi.org/10.1093/cercor/bhj137

Neither stress/exercise

I. 19 healthy female, and 12 healthy male, adults between 19 and 32 years;
II. fMRI used, with regions within the PFC among the regions investigated;
III. **Stress was not experimentally manipulated**;
IV. **The dual-task processing component of executive functioning assessed**;

Forbes, C. E., & Leitner, J. B. (2014). Stereotype threat engenders neural attentional bias toward negative feedback to undermine performance. *Biological Psychology*, *102*(1), 98–107. https://doi.org/10.1016/j.biopsycho.2014.07.007

Stress

I. 40 healthy female adults between 18 and 21 years of age;
II. EEG used, with regions within the PFC among key regions;
III. **The experimental manipulation concerned stereotype threat**;
   a. Their paradigm, in which the participants solved math problems with (or without) negative feedback about their performance, mirrors paradigms intended to induce an acute state of psychosocial stress. Their paradigm used has not been, however, used to induce acute psychosocial stress, and saliva assessments were unassessed (to confirm successful stress induction);
IV. **Core components of executive functioning were unassessed**;

Gärtner, M., Rohde-Liebenau, L., Grimm, S., & Bajbouj, M. (2014). Working memory-related frontal theta activity is decreased under acute stress. *Psychoneuroendocrinology*, *43*, 105–13. https://doi.org/10.1016/j.psyneuen.2014.02.009

Stress

I. **31 healthy male adults between 20 and 50 years of age**;
II. EEG used, with regions within the PFC and salivary cortisol;
III. Stress was experimentally manipulated using aversive films;
   a. Successful stress induction was qualified by higher salivary cortisol responses during the stress condition, relative to control. As stress was a within-subjects factor, however, **both conditions occurred on the same day spaced about 20 mins apart**;
   b. Stress: Irréversible by Gaspard Noé; Control: Comment j'ai tué mon père by Anne Fontaine;
IV. Working memory, as assessed by 0-, 2-, and 3-back conditions of the n-back task, was assessed during the aversive and neutral film (stress and control, respectively). Similar with other previous studies (i.e., Qin et al., 2009, 2012) "Irréversible" by Gaspard Noé was used to induce an acute state of psychological stress;

Gathmann, B., Schulte, F. P., Maderwald, S., Pawlikowski, M., Starcke, K., Schäfer, L. C., Schöler, T., Wolf, O. T., & Brand, M. (2014). Stress and decision making: neural correlates of the interaction between stress, executive functions, and decision making under risk. *Experimental Brain Research*, *232*(3), 957–73. https://doi.org/10.1007/s00221-013-3808-6

Stress

I. 38 healthy participants between 18 and 39 years of age;
II. fMRI used. Also included PFC regions as well as salivary cort.;
III. Stress was experimentally manipulated using the Trier Social Stress Test;
   a. Successful stress induction qualified through salivary cortisol elevations among participants exposed to the Trier Social Stress Test relative to those whom were instead exposed to the placebo version of the paradigm (Het et al., 2009);
   b. Where stress was a between-subjects factor, cognitive assessment administered only following the stress/control induction (participants practiced the cognitive tests before the stress/control treatment, but **no pre-stress/control data**);
IV. Working memory, as assessed by a 2-back condition of the n-back task, was assessed within, and independent of, a decision-making task (Game of Dice Task, in which the participant makes gambling decisions based on the probability of gaining or losing $);

Giles, G. E., Brunyé, T. T., Eddy, M. D., Mahoney, C. R., Gagnon, S. A., Taylor, H. A., & Kanarek, R. B. (2014). Acute exercise increases oxygenated and deoxygenated hemoglobin in the prefrontal cortex. *NeuroReport*, *25*(16), 1320–1325. https://doi.org/10.1097/WNR.0000000000000266

Exercise

I. 10 healthy female, and 14 healthy male, adults aged 20.21 ± 2.38 years – Emailed to confirm the particular age range of participants – Age range: 18 to 29 years;
II. fNIRS used, and regions within the PFC were assessed;
III. Exercise was experimentally manipulated (see below);
   a. Protocol was acute, insofar as it involved 30 min of cycling before 5 min of a cool-down period. Therefore, the entire protocol lasted within 1 h in duration;
   b. Protocol was, in part, moderate as a subset of participants were assigned to a cycling bout at 68% of their maximal heart rate. Note that others were either: assigned to cycle at a light (52%) or heavy (84%);
IV. **Core components of executive functioning unassessed**;

Hall, P. A., Elias, L. J., Fong, G. T., Harrison, A. H., Borowsky, R., & Sarty, G. E. (2008b). A social neuroscience perspective on physical activity. *Journal of Sport and Exercise Psychology*, *30*(4), 432–449. https://doi.org/10.1123/jsep.30.4.432

Exercise

I. 124 adults (Study 1; 19.74 ± 4.53 years; 12.5% male, 87.5% female) and 64 adults (Study 2; 19.03 ± 2.48 years; 25.0% male, 73.4% female, 1.6% missing) – Emailed to confirm age range;
II. No neuroimaging used in Study 1, but Study 2 involved fMRI with PFC regions studied;
III. **Exercise was not experimentally manipulated**. Rather, self-reports of physical activity, in combination with participants wearing an accelerometer during a 1-week period, were used as indicators of physical activity in relation to self-regulatory behaviours;
IV. Inhibitory control, as assessed by the Stroop test, was administered. Of note, the Tower of Hanoi and Go/NoGo tasks were also administered with the Stroop Test. The latter 2 were, however, not reported in the results due to movement artefact during fMRI scanning;

No email correspondence information provided.

*Henckens, M. J. A. G., Hermans, E. J., Pu, Z., Joëls, M., & Fernández, G. (2009). Stressed memories: How acute stress affects memory formation in humans. *Journal of Neuroscience*, *29*(32), 10111-19. https://doi.org/10.1523/JNEUROSCI.1184-09.2009

Stress

I. 18 healthy male adults between 19 and 31 years of age;
II. fMRI used and salivary cortisol assessed; However, the PFC was not among their regions of interest, as the study was primarily interested in the role of the hippocampus in relation to memory formation;
III. Stress was experimentally manipulated through aversive film;
   a. Successful stress induction was qualified by elevations in heart rate and salivary cortisol, and worsened mood, as indicated by the negative affect subscale of the Positive Affect Negative Affect Schedule;
   b. Where stress was a within-subjects variable, an inter-session interval of about ~1 month was used, ensuring that sufficient temporal lag between stress and control exposure was used;
   c. Stress: Irréversible by Gaspard Noé; control: Comment j'ai tué mon père by Anne Fontaine;
IV. **Declarative memory was assessed during the stress / control**. A cued recall paradigm was administered 1 day following stress/control exposure. While memory was generally examined, the study focused on declarative (and, in particular, episodic memory), rather than working, memory;