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Exercise-Induced Cognitive Decline: Exploring the Role of Pain Catastrophizing

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Abstract

The relationship between exercise and cognition has been extensively studied, with results varying based on factors such as the length, intensity, and modality of exercise and the timing, task, and domain of cognition under investigation. While studies evaluating concomitant exercise and cognition overwhelmingly indicate decrements in performance on executive function tasks at high intensities, there remains limited agreement on how individual differences or cognitions might affect the physiological processes linked to these declines. As such, the present prospective, within-subjects study sought to systematically examine the impact of pain catastrophizing, a variable known to impact attentional processes, on the relationship between exercise intensity and executive function. Following completion of a series of online questionnaires and familiarization procedures (Visit 1), eligible participants completed an executive function test, the Cedar OWAT, while simultaneously completing a graded maximal exercise test on a treadmill (Visit 2). Results indicated significant decrements in executive function performance as exercise intensity increased, with pain catastrophizing interacting with exercise intensity to exert differential effects on hit rate and precision. In summary, the present study replicates previous findings demonstrating a significant negative relationship between exercise intensity and executive performance and offers initial evidence that higher levels of pain catastrophizing could contribute to complex alterations in cognitive performance under such conditions. These findings should be further explored in future studies, as they might hold particular relevance in settings in which maintaining peak cognitive abilities is crucial for effective decision-making, performance, and overall health.

Keywords: executive function, exercise intensity, pain catastrophizing

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Introduction

Cognition During Exercise: The Importance of Specificity

The influence of exercise on cognition has been a topic of study for nearly half a century (Tomporowski & Ellis, 1986). Although the subject has been extensively researched, the field is characterized in part by vast variations in methodology and theoretical frameworks. Studies have varied by factors such as general design (i.e., between versus within groups), exercise protocol (i.e., length, intensity, and modality), and application of cognitive testing (i.e., timing, task, and domain of cognition assessed).

Considering that variables such as length, intensity, and exercise modality vary widely in applied settings, it seems logical and prudent to systematically study how these variables may impact cognition under a wide range of circumstances. Although many studies have explored targeted subsets of these variables, the inconsistency in experimental approaches has led to findings that, at first glance, appear somewhat discrepant. These disparities have made it challenging for researchers to make broad conclusions about the impact of exercise on cognition. However, a careful examination of the evidence suggests that the relationship between exercise and cognition is best understood when comparisons are narrowed according to factors such as the intensity and duration of exercise or the type or timing of cognitive testing.

Executive Function

In general, most studies seeking to describe the impact of physical activity on mental performance focus specifically on the effortful, higher-order cognitive processes collectively referred to as executive function (Diamond, 2013). Executive function is comprised of a set of "core" mental processes, typically considered to be inhibition, working memory, and cognitive flexibility, that allow for reasoning, problem-solving, and regulation of emotion and attention. Efficient executive function is crucial for effectively managing day-to-day tasks, including planning, prioritizing, and adapting to changing circumstances. With this in mind, it is perhaps unsurprising that high levels of executive function are closely linked with success across nearly all domains of life (Diamond, 2013). The need for optimal levels of executive function makes it an attractive target for experimental investigations, as a better understanding of factors that might either degrade or enhance EF is of immense ecological importance in a broad range of applied settings.

Exercise Intensity

Although it is generally accepted that exercise impacts EF, the vast body of literature on the topic is characterized by significant heterogeneity in findings. For example, there is a myriad of research indicating that chronic exercise is associated with enhancements in cognition (Etnier et al., 1997; Landrigan et al., 2020; Liu et al., 2020; Vazou et al., 2019), particularly in groups experiencing cognitive deficits (Duchesne et al., 2015; Firth et al., 2016; Huang et al., 2019; Lu et al., 2023; Marino et al., 2023, p. 20; Nuechterlein et al., 2023; Yang et al., 2024) or in aging populations (Bliss et al., 2021; Festa et al., 2023; Noguera et al., 2019; Shi et al., 2024; Xu et al., 2023; G. Zheng et al., 2016). However, studies evaluating the impact of acute physical exertion on cognition are less clear-cut, with some debate as to whether exercise plays an inhibitory or facilitatory role (K. Zheng et al., 2021).

On the one hand, some studies have shown improvements in executive function with acute exercise (Dodwell et al., 2018; Joyce et al., 2009; Komiyama et al., 2015, 2017; Lucas et al., 2012; Martins et al., 2013; Ogoh et al., 2014; Olson et al., 2016; Schmit et al., 2015). Of the studies measuring cognitive performance concurrently with exercise, improvements in executive function were most commonly demonstrated at moderate intensity levels (Joyce et al., 2009; Komiyama et al., 2015, 2017; Martins et al., 2013; Ogoh et al., 2014; Olson et al., 2016), based on the classifications of exercise intensity laid out by Norton et al. (2010). These findings support the supposition that cognitive performance during exercise follows an inverted-U pattern, by which moderate-intensity exercise will induce the most favorable cognitive enhancements (Chang et al., 2012); however, these results are not equivocal, with an even larger number of studies focused on moderate-intensity exercise and executive function returning non-significant results (Audiffren et al., 2009; Davranche & McMorris, 2009; Joyce et al., 2014; Komiyama et al., 2015, 2017; Lambourne et al., 2010; McMorris et al., 2009; Pontifex & Hillman, 2007; Smith et al., 2016; Stone et al., 2020; Wang et al., 2013).

EF enhancement has also been reported during vigorous-intensity exercise (Dodwell et al., 2018; Lucas et al., 2012; Schmit et al., 2015). Schmit and colleagues (2015) utilized a Flanker task to evaluate the impact of steady-state cycling at 85% to exhaustion on inhibitory control. Notably, the average duration of exercise was about 7 minutes. Results indicated an initial significant boost in reaction time, which remained unaltered into the final stages of exercise. However, the propensity to make impulsive errors was increased near exhaustion. Dodwell et al. (2019) also utilized a biking condition, but exercise intensity was maintained at 65% and compared to a treadmill walking condition. While active conditions were designed to allow for cardiovascular exertion, authors noted that treadmill pace and bike resistance levels were chosen based on previous literature to maintain subject comfort (beyond increases in heart rate). Performance on a retro-cue working memory task was facilitated in both cycling and treadmill compared to control conditions; however, this finding was significantly impacted by postural factors, with authors postulating that upright orientation, compared to seated conditions, might play an independent role on cognitive performance.

In contrast, a larger portion of the research evaluating this relationship indicates that acute exercise—particularly high-intensity exercise—is associated with concomitant decrements in performance on EF tasks (Audiffren et al., 2009; Davranche & McMorris, 2009; Del Giorno et al., 2010; Dietrich & Sparling, 2004; Komiyama et al., 2019; McMorris et al., 2009; Olson et al., 2016, 2016; Pontifex & Hillman, 2007; Smith et al., 2016; Stone, 2020; Wang et al., 2013). Executive function attrition is most commonly associated with moderate (Audiffren et al., 2009; Davranche & McMorris, 2009; Del Giorno et al., 2010; Olson et al., 2016; Pontifex & Hillman, 2007) to vigorous exercise (Dietrich & Sparling, 2004; Komiyama et al., 2019; McMorris et al., 2009; Smith et al., 2016; Stone et al., 2020; Wang et al., 2013), though some studies have also revealed declines in executive function have also been demonstrated during light-intensity exercise (Del Giorno et al., 2010; Olson et al., 2016).

When comparing the findings of the studies citing improvements in performance during "vigorous" exercise to those demonstrating decline, it becomes apparent that only the study conducted by Schmit and colleagues (2015) was conducted at an intensity comparable to the level at which decrements became significant (i.e., 80% HRR) in the study conducted in 2020 by Stone et al. This is a potentially meaningful consideration, as Stone and colleagues (2020) remain the only published study to have monitored executive function continuously across exercise intensity instead of asking participants to maintain a specific intensity for the duration of exercise or measuring cognition at set, discrete intervals. Likewise, the investigations conducted by Lucas et al. (2012) and Schmit et al. (2015) involved an exercise of relatively short duration, with time spent at vigorous intensities totaling less than ten minutes. Given that Schmidt et al. (2015) noted a steep, though non-significant, decrease in cognitive control immediately prior to test cessation, it is reasonable to consider that results might have reached significance had the duration of exercise been longer; this supposition is strengthened by linear decreases in cerebral oxygenation measured by fNIRS throughout exercise (Schmidt, 2015). Likewise, while Dodwell et al. (2018) did not report the time span of exercise, the intensity did not exceed 65% HRR, which was well below the onset of decline demonstrated by Stone et al. (2020). It is important to consider that these differences in experimental paradigms are almost certainly responsible for the marked differences between these three studies and the numerous others demonstrating degradation of EF at high intensities when measured concomitantly with exercise.

Significantly, the supposition that cognition will suffer during high-intensity exercise is underpinned by sound theoretical backing. Specifically, these findings align with theoretical positions modeling aspects of cognition as belonging to a limited resources system (Gailliot, 2008; Matthews, 2009; Matthews et al., 2000; Wickens et al., 2015). This perspective posits that individuals have a bounded capacity to meet cognitive demands, and performance decrements occur when the task demands exceed the available resources. This perspective is strengthened by the physiological evidence that the brain operates using a finite supply of energy (Attwell & Laughlin, 2001; Bruckmaier et al., 2020; Lennie, 2003). Thus, the more energetically expensive a task, the fewer resources available for processing or attending to concurrent tasks or additional environmental stimuli.

Due to the effortful nature of EF, activation and utilization of the EF systems, compared to the cognitive processes considered to be automatic or unconscious, are more energetically costly (Gailliot, 2008; Tomasi et al., 2013). Notably, exercise exacts heavy bioenergetic tolls, and the idea that the competition of these processes has been speculated to underlie the tradeoffs between cognition and maintenance of exercise at high intensities has received empirical support (Dietrich & Audiffren, 2011; Stone et al., 2020).

Variations in During and Post-Exercise Task Administration

The timing of cognitive task administration must also be considered in addition to intensity when differentiating between studies focused on the impact of acute exercise. While a relatively recent meta-analysis conducted by Moreau and Chou (2019) lent some support for cognitive enhancement with vigorous acute exercise, it is important to note that their inclusion criteria stipulated that executive function tasks be administered *after* the bout of exercise, with a primary study hypothesis centering on cognitive performance at least one minute following exercise cessation.

Although these findings, which corroborate the results of Chang and colleagues (2012), appear to support a small enhancement of exercise of cognition in the acute post-exercise period, it is important to consider that this finding in no way negates the studies demonstrating significant decrements in executive function *during* exercise. Given the proposed mechanisms by which vigorous activity induces cognitive decline, it is reasonable to consider that the cessation of exercise would allow for a decreased drain on the mental and physiological resources previously utilized to sustain high-intensity movement.

For example, research indicates that initial heart rate recovery in the immediate post-exercise period is rapid, particularly in healthy adult populations; this initial steep decrease in heart rate signals the transition back toward physiological homeostasis via both gradual decreases of sympathetic activation and reactivation of parasympathetic control (Borresen & Lambert, 2008; Coote, 2010; Peçanha et al., 2014). While it is understood that energy demands remain elevated following exercise (Børsheim & Bahr, 2003; Powers & Jackson, 2008), these levels are still far lower than the immediate metabolic resources required to continue high-intensity exercise, both due to decreases in the mental and physiological demands associated with high-intensity exercise (Dalsgaard et al., 2003). Similarly, the discomfort associated with maximal exercise begins to subside when exercise is halted, considering pain and discomfort have also been shown to interfere with cognitive performance (Lier et al., 2022), with these deficits becoming particularly salient when the degree of resources needed to accomplish the cognitive task is high (Wagenaar-Tison et al., 2022), the uncomfortable nature of the exercise is likely to elicit differential effects at high intensity compared to even to the few minutes following exercise.

Considering the sound physiological principles that could account for the consistent differences in conclusions regarding executive function measured during versus immediately following acute bouts of vigorous activity, it is logical to consider the impact of acute bouts of exercise during and following exercise separately.

Identifying Patterns and Drawing Conclusions

The extant research in this domain points to a complex and heterogeneous relationship between exercise and cognition impacted by multiple factors, including the nature of the exercise under investigation, aspects of the cognitive task, and individual differences of the participants. When critically examined based on the aforementioned factors, a few primary conclusions about the acute exercise and cognition relationship can be made:

1. Executive function enhancement may occur during low-moderate intensity exercises under some conditions and following high-intensity exercise when testing occurs at least one minute following cessation.

2. Executive function degradation is likely present during high-intensity exercise, particularly at intensities above 80% when cognition is measured concomitantly with exercise.

While additional research must be conducted to further delineate the impact of exercise on discrete domains of executive function and variations in findings based on the type of exercise under investigation, these conclusions provide a starting point from which to begin applying the basic science investigations of exercise and cognition to more applied questions in specific settings. However, this process comes with the caveat that researchers must ensure their experimental parameters adequately mirror the demands and conditions of the environments to which they seek to inform and appropriately acknowledge the circumstances to which their results can be extrapolated. For example, applying results demonstrating enhancements in cognition in the minutes following exercise will likely not adequately provide insight for settings where cognition is vital amid extreme exertion.

Mitigating Cognitive Decline: Relevance to Applied Settings.

Research evaluating executive function during exercise is important for anyone frequently engaging in vigorous physical activity. Similarly, the demonstrated declines in executive function are particularly troublesome for individuals employed in professions where the need to maintain a high cognitive function is often coupled with intense physical exertion. Such fields include professional athletics, first responder teams, and the military. Optimal cognitive and physical performance is particularly crucial for members of safety-sensitive occupations, as they are often expected to make swift assessments and decisions under extreme pressure. In these settings, performance reductions in reaction time, inhibitory control, working memory, or cognitive flexibility could result in catastrophic consequences. Optimal performance is often crucial not only for operational success but also for preventing casualties.

Identifying Target Variables: The Potential Role of Pain Catastrophizing

While several studies have established a link between vigorous exercise and executive function degradation, further research is needed to understand better what variables might interact with or mediate the relationship between exercise and cognition. Ultimately, the goal is to identify viable variables that may be targeted to help buffer exercise-related cognitive decline.

One method of identifying potential mediators and moderators is exploring the causes of individual variation across the variables in question. Studying individual differences is crucial in developing theoretically sound explanations for potential mediation or moderation models, thus advancing plausible intervention strategies (Beaujean, 2008). The use of mediation and moderation models to study early intervention programs is well-established (Breitborde et al., 2010). Several validated statistical methods are designed to pinpoint potential targets for buffers and applied solutions as an attractive option (Breitborde et al., 2010; Hayes & Rockwood, 2017; Hopwood, 2007).

With this in mind, working to explain what characteristics might make specific individuals more resistant or susceptible to cognitive decline during exercise compared to others is a reasonable endeavor. Importantly, there do seem to be individual differences in the level of cognitive decline experienced by individuals during high-intensity exercise. While Stone et al. (2020) demonstrated significant decreases across participants in executive function as exercise intensity, measured as heart rate reserve (HRR%), approached 80% and above, there was variation in the exact onset of decline between participants. This is consistent with a wide array of research indicating that considerable individual differences exist between cognitive performance and other variables reported to produce decrements in cognition, such as fatigue, stress, or changes in workload (Matthews, 2009; Matthews et al., 2000, 2012).

Pain Catastrophizing Defined

Given the theoretical underpinnings of the relationship between exercise and cognitive decline, it is logical to prioritize assessing factors associated with aberrations in attention, as such variables might subsequently predispose individuals to increased depletion of finitely available neural resources during vigorous activity or mentally challenging tasks. Individual differences in responses to discomfort also serve as a reasonable starting point when considering potential interacting constructs, as such differences are both well-demonstrated empirically and of particular relevance in light of the often-uncomfortable nature of exercising at high intensities. With this in mind, pain catastrophizing, a construct increasingly recognized as significantly impacting both attentional processes relating to pain, as well as a number of important health-related outcomes, likely fits this description.

Although "catastrophizing" has most commonly been discussed in relation to pain, its original conceptualization was broader, used to describe the tendency to hold unfounded and fatalistic outlooks on any possible future event (Beck et al., 1985; Ellis, 1962). This construct was later narrowed to apply specifically to thoughts and feelings related to pain, with pain catastrophizing defined as "an exaggerated negative mental set brought to bear during actual or anticipated pain experience" (Sullivan et al., 1995). Although some researchers have critiqued the utility of and the theoretical framework for this definition (Crombez et al., 2020; Leung, 2012; Petrini & Arendt-Nielsen, 2020), it has been the primary conceptualization for the vast majority of research in this domain since its initial description and has allowed for a transdiagnostic biopsychosocial approach to pain and pain-related outcomes (Gellatly & Beck, 2016; Simic et al., 2024; Sullivan & Tripp, 2024).

Importantly, pain catastrophizing has been extensively explored and has been consistently demonstrated to be one of the most robust psychological predictors of increased adversity related to the pain experience (K. M. Edwards et al., 2006; Sullivan et al., 2001; Sullivan & Tripp, 2024; Traxler et al., 2019; Weissman-Fogel et al., 2008). Individuals endorsing higher levels of pain catastrophizing are more likely to experience chronic pain (Fisher et al., 2018; Martinez-Calderon et al., 2019), opioid misuse (Arteta et al., 2016) extreme postoperative pain (Khan et al., 2012), activity intolerance (Sullivan et al., 2002; Zhaoyang et al., 2020), poorer responses to rehabilitative therapies (Uckun et al., 2020), and lower quality of life (Börsbo et al., 2010), along with a host of other health-related outcomes. It is multidimensional in nature, considered to involve both cognitive and affective features, and is characterized by pain-related rumination, magnification, and helplessness (Leung, 2012; Sullivan, 1995).

Although pain catastrophizing has been associated with other conditions that are also often considered to involve enhanced attention to negative stimuli or heightened levels of worry, such as anxiety (Leeuw et al., 2007) and neuroticism (Crombez et al., 2002), empirical evidence suggests that it is a discrete construct that has been shown to predict outcomes related to pain independently (Crombez et al., 2002; Goubert et al., 2004; Lackner & Quigley, 2005; Legarreta et al., 2016; Sullivan et al., 1998). While commonly associated with clinical populations, it is important to note that pain catastrophizing has been demonstrated in otherwise healthy samples, although at a lower prevalence than is typically seen in those with chronic pain or other illness or injury (R. R. Edwards et al., 2004).

Conceptual Challenges

Although some pain scholars have suggested that pain catastrophizing may just be “an extreme instance of worrying” (Crombez et al., 2020; Petrini & Arendt-Nielsen, 2020), studies that have demonstrated an independent effect of pain catastrophizing on health-related outcomes in the absence of other indices of worry suggest otherwise (Crombez et al., 2002; Lackner & Quigley, 2005; Sullivan et al., 2009; Sullivan et al., 1998). While the claim that pain catastrophizing is better conceptualized as extreme worry is not currently well-supported empirically, it does highlight an essential controversy in the pain literature arena related to the lack of an all-encompassing theoretical framework for pain catastrophizing (Sullivan & Tripp, 2024). While the complexity of the construct has made unified explanations challenging, this has not prevented pain catastrophizing from having immense clinical utility. Likewise, while some have critiqued the conceptualization, there are a number of theoretical positions that have been posited to explain aspects of pain catastrophizing.

Existing Frameworks

Schema-Activation Model. According to the Schema-Activation model, cognitive schemata related to pain are hyper-active in individuals high in pain catastrophizing (Leung, 2012; Sullivan et al., 2001). When these schemas are activated, a cascade of negative thoughts, emotions, and physiological reactions associated with pain impact the subsequent perception of and experience with whatever stimuli activated the schema, thus predisposing these individuals to overly pessimistic outlooks and learned expectancies of pain. These schemas are typically considered to bias maladaptive responses to pain, as their activation leads to exaggeratedly negative assessments, cognitive distortions, and continued rumination on previous pain experiences.While this model highlights the cognitive component of pain catastrophizing, the presence of schemas can be empirically challenging to evaluate, and this model may not entirely account for the multifaceted nature of catastrophizing (Lueng 2012, Sullivan, Bishop, Pivik, 1995; Sullivan et al., 2001).

Appraisal Model. The Appraisal Model of pain catastrophizing stems from classical psychological models contextualizing stressors in terms of the perceived ability to deal with that stressor (Lazarus & Folkman, 1984). In pain catastrophizing, the Appraisal Model posits that individuals high in pain catastrophizing appraise pain-related stimuli as threatening, above and beyond what might be appropriate for the situation or the context (Leung, 2012). Although there is some evidence that threat appraisal may be a relevant component of pain catastrophizing for some individuals in some situations (Anderson & Hanrahan, 2008; Stroud et al., 2000), aberrations in threat appraisal are only one of various other maladaptive cognitive processes associated with pain catastrophizing, from appraisal of threat, have been associated with pain catastrophizing. As such, this model is unlikely to capture the construct as it is currently understood.

Attention-bias model. The attention bias model suggests that pain catastrophizing is a maladaptive cognitive response that leads to heightened attention to pain-related stimuli or the possibility of experiencing pain-related stimuli, which then spurs maladaptive alterations in cognitive or behavioral inhibition (Asefi Rad & Wippert, 2024; Eccleston & Crombez, 1999; Michael & Burns, 2004; Quartana et al., 2009; Sullivan et al., 1995; Van Damme et al., 2002, 2004, p. 2; Vancleef & Peters, 2006). A number of studies have demonstrated preferential attention to pain-related information by those scoring higher on pain catastrophizing measures (Spanos et al., 1979; Chaves and Brown, 1987; Eccleston et al., 1999; Van Damme et al., 2002 & 2004; Van Cleef et al. 2006 Michael et al. 2004, Quartana et al., 2009; Sillican, 1995), and these findings are further strengthened by studies demonstrating that analgesic distraction methods are less effective for individuals high in pain catastrophizing, indicating that not only are these individuals likely to have a heightened awareness for pain-related stimuli, but they will also struggle to disengage their attention from such stimuli, even in the presence of a distraction (Asefi Rad & Wippert, 2024). While this model has received the most empirical support, as with the others, it does not completely capture the affective components or fully explain the neurophysiological correlates associated with pain catastrophizing (Leung, 2012).

Neurobiological Mechanisms

Although the neurobiological mechanisms underlying the construct are still being elucidated, several potential biomarkers and physiological processes have been associated with pain catastrophizing in the last decade. For example, multiple twin studies and investigations of specific genetic variations have made a strong case for the heritability of pain catastrophizing (Alves et al., 2020; Burri et al., 2018; Horjales-Araujo et al., 2013; Trost et al., 2015). Polymorphisms in the 3B serotonin receptor (Horjales-Araujo et al., 2013) and the brain-derived neurotrophic factor gene (i.e. Val66Met substitution; Alves et al., 2020) have been linked to increased susceptibility to pain catastrophizing and are proposed to underlie deviations in both the processing of and ability to cope with pain.

Similarly, several brain areas are implicated in pain catastrophizing, including the Anterior Cingulate Cortex (ACC; Galambos et al., 2019; Gracely et al., 2004), the Dorsolateral (DLPF) and Ventromedial Prefrontal Cortices (MPF; Blankstein et al., 2010; Galambos et al., 2019; Gracely et al., 2004; Seminowicz & Davis, 2006), and the premotor cortex (Seminowicz & Davis, 2006). Importantly, the neural pathways typically associated with pain catastrophizing are not those primarily involved with discriminatory or sensory components of pain (i.e. the primary or secondary somatosensory cortex). Rather, pain catastrophizing is most commonly related to deviations in neural activity in areas considered to be responsible for modulating affective, cognitive, and motor responses to pain.

For example, the ACC, known for its role in modulating pain responses and association with emotional processing, has been demonstrated to be hyperactive in individuals reporting high levels of pain catastrophizing (Galambos et al., 2019). Given the importance of the ACC to both directing attention (Bryden et al., 2011; Luks et al., 2002) and to the processing pain (Rainville et al., 1997), hyperactivity in this area helps to explain the difficulty individuals high in pain catastrophizing have with disengaging with painful stimuli. Although not a specific target of investigation, ACC hyperactivity is in line with Cooke and colleagues' (2023) findings related to the relationship between reward processing and pain catastrophizing; while this investigation was conducted completely in the absence of priming or manipulating pain and specifically noted alterations in striatal activation, the ACC is also associated with reward processing, thus providing additional evidence that brain areas involved in affective and cognitive responses, particularly those that might reward avoidance of stimuli that might be presumed to be painful, may strongly influence behavior in those prone to catastrophizing.

Decreased activation in the DLPF and MFC in the presence of painful stimuli and reductions in DLPF grey matter are also associated with increased levels of pain catastrophizing (Blankstein et al., 2010; Ong et al., 2019; Seminowicz & Davis, 2006). The DLPF has been implicated as an important top-down modulator of pain, providing a possible mechanistic explanation for the association between suppression of DLFP activity and dampened ability to disengage from pain-related thoughts seen in pain catastrophizing (Lorenz et al., 2003). These deviations become particularly salient as pain intensity increases, indicating that activation of top-down regulatory mechanisms that were feasibly more available to modulate pain while intensity remained low are shifted toward other processes and areas, particularly those associated with attention to pain and emotional aspects of pain (Gracely et al., 2004; Seminowicz & Davis, 2006). Such findings provide important support for the attentional model of catastrophizing, as they suggest mechanisms by which inability to maintain attention on non-pain related tasks in the presence of pain stimuli might be explained.

Dispositional or Situational Conceptualizations

The pain science arena has also been fraught with discussion as to whether pain catastrophizing should be assessed as a dispositional (trait) or as a situational (state) construct. When extrapolated from previous discussions of more general catastrophizing by Sullivan and colleagues (1995), the construct was discussed primarily as a trait-based quality given the conceptualization of pain catastrophizing as a generally stable predisposition, rather than as a fluctuating characteristic influenced more heavily by situational factors (i.e. as a state construct).

The Pain Catastrophizing Scale (PCS) was developed with this dispositional framework in mind and was validated to assess trait-based catastrophizing in both clinical and non-clinical samples (Sullivan et al., 1995). While more recent measures (i.e. the Pain-Related Cognitive Process Questionnaire, Situational Catastrophizing Scale) have been developed to assess state-based catastrophizing, these measures correlate strongly with those assessing dispositional catastrophizing and may be most appropriate for paradigms in which the goal is for participants or patients to reflect on a specific pain-related experience, such as current chronic pain or a recurrent painful condition (Day et al., 2018, 2021) or when assessing catastrophizing immediately following the experimental application of a painful stimulus (Birnie et al., 2016).

Although dispositional characteristics are considered by definition to be stable, it’s important to acknowledge that there is plenty of evidence indicating that generally stable traits can change over time, often in the presence of impactful events (Bleidorn et al., 2018; Hall & Wilson, 2007) or of targeted interventions, such as those geared toward long term reductions in neuroticism (Jorm, 1989; Roberts et al., 2017). While the act of catastrophizing pain can impact the experience or anticipation of pain, exposure to pain can also give rise to catastrophic thinking (Campbell et al., 2010; Crawford et al., 2021; Gopinath et al., 2019; Sullivan et al., 2001; Sullivan & Tripp, 2024). This supports the idea that the relationship between the experience of pain and pain catastrophizing is bidirectional and that pain catastrophizing, while demonstrated to be relatively stable in some samples, is a malleable construct that personal experiences can influence long-term.

Identifying Patterns and Drawing Conclusions: Pain Catastrophizing

The current body of literature exploring pain catastrophizing points to a multifaceted construct with wide-ranging implications for pain- and performance-related outcomes (Sullivan & Tripp, 2024). A comprehensive understanding of pain catastrophizing likely requires acknowledging a complex interplay between cognitive processes, emotional responses, social dynamics, and situational factors.

Although the attention-bias model seems to have received the most empirical support of the existing models, it is important in this case not to dismiss the potential value of the other conceptualizations. As is the case with many complex and multidimensional constructs, it is likely unhelpful to attempt to pigeon-hole pain catastrophizing into a framework that captures limited aspects of the phenomenon; instead, the multifaceted nature of pain catastrophizing demands a multifaceted explication that highlights the key features of the construct while still accounting for the diversity of contributing mechanisms. In general, it is important to keep in mind that all proposed models of catastrophizing attempt to address, with slightly different conceptualizations, the tendency of individuals high in pain catastrophizing to experience exaggeratedly negative thoughts or feelings related to pain, to excessively ruminate on those thoughts and feelings, and to experience some degree of helplessness or maladaptive coping strategies when confronted with or anticipating pain. As is the case with the relationship between cognition in exercise, context is important, and current experimental approaches should highlight how each research paradigm is related to the current frameworks and how biological, cognitive, emotional, and social factors interact and contribute to the experience and expression of pain catastrophizing within the context of the specific research question.

Attentional Demands and Performance Decrements: Catastrophizing in Applied Settings

Although attending to pain-related thoughts and stimuli is generally adaptive (Eccleston & Crombez, 1999), the capacity to suppress such cognitions is at times critical for allowing individuals to attend to other important environmental stimuli or ongoing tasks (Legrain, Damme, et al., 2009; Legrain et al., 2013; Legrain, Perchet, et al., 2009; Moore et al., 2012) (Legrain, Damme, et al., 2009; Legrain et al., 2013; Legrain, Perchet, et al., 2009; Moore et al., 2012). Like maintaining high levels of physical performance and executive function, the ability to divert thoughts away from physical discomfort is often required in safety-sensitive and athletic populations.

While it is perhaps counterintuitive to some that pain catastrophizing would be common enough in individuals employed in settings known for involving frequent experience of discomfort to warrant further inquiry, there is a wealth of evidence demonstrating the presence of pain catastrophizing in military (Ciccone et al., 2010; Judkins et al., 2022; Kegel et al., 2023; Schaaf et al., 2023; Spevak & Buckenmaier, 2011) athletics (Gagnon-Dolbec et al., 2021; Paparizos et al., 2005; Sciascia et al., 2020; Sullivan et al., 2000).

In military samples, there is evidence to indicate that pain catastrophizing can be an important factor in chronic pain experienced during service (Ciccone et al., 2010; Schaaf et al., 2023), poorer outcomes following traumatic brain injury (Hoffman et al., 2019), (Hoffman et al., 2019)or psychological distress (Ciccone & Kline, 2012) for currently-serving National Guard (Ciccone et al., 2010) or other active-duty military members and veterans (Spevak & Buckenmaier, 2011). Importantly, it has been demonstrated to be present in these populations even in the absence of existing pain-related conditions, and there is evidence to indicate that it could be a key barrier to entry, preventing specific individuals from making it through the initial training periods (Judkins et al., 2022).

Furthermore, as these occupations are also more likely to entail an increased risk of injury, exposure to extreme conditions or on-the-job hazards, and higher rates of psychological distress, those engaging in safety-sensitive or physically demanding work may be at increased risk of experiencing conditions that are associated with the development or exacerbation of pain catastrophizing during the course of their employment. This is concerning, as those with high levels of pain catastrophizing are less likely to return to service and more likely to qualify for both short-(Hiebert et al., 2012) and long-term work-related disability (Schaaf et al., 2023; Spevak & Buckenmaier 2011). These findings also hold true for athletic populations, with vastly lower return-to-sport rates following injury in players who experience higher levels of pain catastrophizing (Browning et al., 2021; Jochimsen et al., 2020).

Importantly, those individuals higher in pain catastrophizing who do return to serve or to their sport are at risk of experiencing significant cognitive and physical performance-related deficits upon their return. Pertinent to the present investigation, individuals high in PC appear to experience pain-related disruptions in exercise (Nijs et al., 2008; Zhaoyang et al., 2020), particularly if they are also high in anxiety sensitivity (Goodin et al., 2009). Likewise, evidence indicates that PC attenuates cognitive function (Galvez-Sánchez et al., 2018; Legarreta et al., 2016; Tabry et al., 2020; Ysidron et al., 2021). The worsened performance of individuals who tend to catastrophize is theorized to partially stem from an inability to divert focus away from their pain-related cognitions (Lee et al., 2018; Sullivan et al., 1995).

This inability is particularly problematic in light of the aforementioned need to maintain vigorous activity while simultaneously sustaining optimal cognitive levels in these populations. Given the difficult and sometimes physically unpleasant nature of exercise, particularly high-intensity exercise, it is reasonable to explore the possibility that individuals with weakened resource allocation skills might experience more significant decrements in cognition and exercise performance as task demands increase. Given that PC is associated with a heightened tendency to attend to and process pain-related information, it seems possible that individuals high in PC might experience decrements in cognition above and beyond what individuals low in PC might experience during high-intensity exercise. research that can either inform potential interventions evaluate the buffering effects of these exercise-induced decrements in cognitive function is imperative. Importantly, this would be the first study to assess the impact of pain catastrophizing on the relationship between exercise intensity and cognition.

Study Goals and Hypotheses

With the observations above and the existing literature in mind, the current study proposed to:

1) Evaluate the interaction between exercise intensity, cognition, and pain catastrophizing.

   Primary Hypothesis: Pain catastrophizing will moderate the relationship between exercise and cognition, with higher levels of pain catastrophizing resulting in more significant decrements in cognition. Individuals high in pain catastrophizing will experience greater, more rapid declines in cognitive performance.

2) Serve as the second study (Stone et al,. 2020) to demonstrate that cognitive performance decreases as exercise intensity increases when cognition is measured continuously across exercise from baseline to volitional failure.

    Secondary Hypothesis: Cognitive performance will decrease as exercise intensity increases. Specifically, hit rate and precision will decrease as exercise intensity is measured as %HRR increases for all participants.

Method

Design

The present study utilized a within-subjects design to evaluate the degree to which pain catastrophizing impacted cognitive performance across exercise intensity. Data collection involved online questionnaires, survey components, and in-person measurements of physiological and cognitive variables.

Participants

Based on a power analysis conducted via G*Power 3.1 and previously reported effect sizes (Del Giorno et al., 2010; Wang et al., 2013), a sample size of 27 was required to achieve 80% power (Cohen, 1988). Participants were recruited via flyers, posted across campus, and distributed digitally by willing course instructors, in-person recruitment in willing instructors' courses and at registered student organization meetings, the Psychology Department SONA subject pool, and word of mouth.

Prior to enrollment in the study, individuals interested in participating were screened using the Physical Activity Readiness Questionnaire (PAR-Q) and a general Health Status

Questionnaire. Those who answered “yes” to any of the questions on the PAR-Q or who reported cardio-metabolic conditions on the health questionnaire, including hypertension, diabetes, history of stroke or heart attack, coronary artery, neurodegenerative, or kidney disease, or other conditions that might make maximal exercise unsafe were not invited to participate in the in-person visits.

Measurement Tools

Questionnaires and Forms

Health Insurance Portability and Accountability Act (HIPPA). Given the need to collect a medical history, HIPPA forms were utilized to explain the purpose of collection, methods of data storage, access to data by research staff, and participants’ rights to data. Signed copies of the HIPPA form were obtained following the in-person consent process and were stored in a lock box for the duration of collection.

Health Status and Exercise History Questionnaire. A health status questionnaire adapted from the Human Circulatory Research Lab Health Status Questionnaire was utilized to gather general demographic information and relevant medical and exercise history (Stone et al., 2020). Responses were then screened to ensure potential participants were healthy enough for exercise. Individuals with a history of:

a) hypertension
b) diabetes
c) stroke
d) heart attack
e) coronary artery
f) neurodegenerative disorders

g) kidney disease
h) currently pregnant
i) currently taking blood pressure medication

were excluded from participation. Participants who reported health conditions not explicitly included in the exclusionary criteria and not considered absolute contraindications to exercise were contacted on a case-by-case basis to ensure safety of participation.

The Physical Activity Readiness Questionnaire (PAR-Q). The PAR-Q assessed whether individuals should consult their physician before beginning a new exercise program. Its original validation report (Chisholm et al., 1975) indicated high sensitivity and specificity to detect potential health risks associated with increased physical activity. Slight revisions to the wording were applied in 2002 by an Expert Advisory Committee assembled by the Canadian Society for Exercise Physiology, and it remains one of the foremost pre-exercise screening tools (Shephard, 2015). Importantly, health risks such as poor cardiovascular outcomes are well-predicted by responses to the PAR-Q, according to a longitudinal study completed by the Surveillance and Risk Assessment Division of the Public Health Agency of Canada (Arraiz et al., 1992).

Vigorous exercise may not be appropriate for individuals who respond in the affirmative to the questions included on the questionnaire. Thus, those individuals were excluded from participation to mitigate risks and maintain participant safety. The questionnaire consists of 7 questions and takes less than five minutes to complete.

Pain Catastrophizing Scale (PCS). The PCS was devised to assess individuals' levels of catastrophic thinking about pain. Prior investigations of pain catastrophizing and pain experience were used to compile the items, and factor analyses have revealed three primary constructs:

rumination, magnification, and helplessness. It consists of 13 Likert-style items with high internal consistency (rumination: α = .87; magnification: α = .66; helplessness: α = .78; total PCS: α = .87; Sullivan et al., 1995) and can be completed in five minutes or less.

The questionnaire directs participants to consider occasions in which they've experienced pain and then indicate the degree to which they endorsed a list of thoughts and feelings about pain, with 0 meaning "not at all" and four meaning "all the time." For example, item one reads, "I worry all the time about whether the pain will end" (Sullivan, 1995). It is scored by summing the responses, with higher responses indicating higher levels of pain catastrophizing.

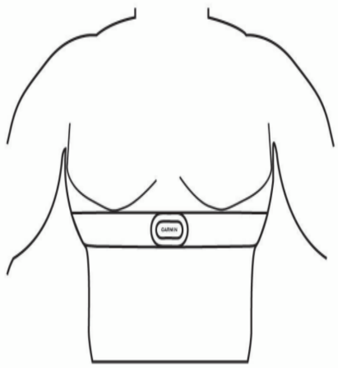
Given the timing of the administration of the pain catastrophizing assessment and the nature of the primary research question under investigation in the present study, utilizing the PCS to evaluate pain catastrophizing from a dispositional perspective is most appropriate.

Physiological Instruments

Garmin HRM-PRO PLUS™. A Garmin chest measured and stored real-time heart rate (HR) data for the duration of the graded exercise task. The strap was positioned around the torso, just below the sternum, with the Garmin logo facing upward. Adjustments to the strap size were made before the initiation of each test to ensure a snug but unrestrictive fit.

Figure 1

Garmin HRM-PRO Placement



To assess HR in real-time, the strap was paired with a performance analytics application, STRAVA, and displayed on an iPad. Each GXT was recorded as an activity in STRAVA, allowing for the export and analysis of each participant's de-identified data on a second-by-second basis.

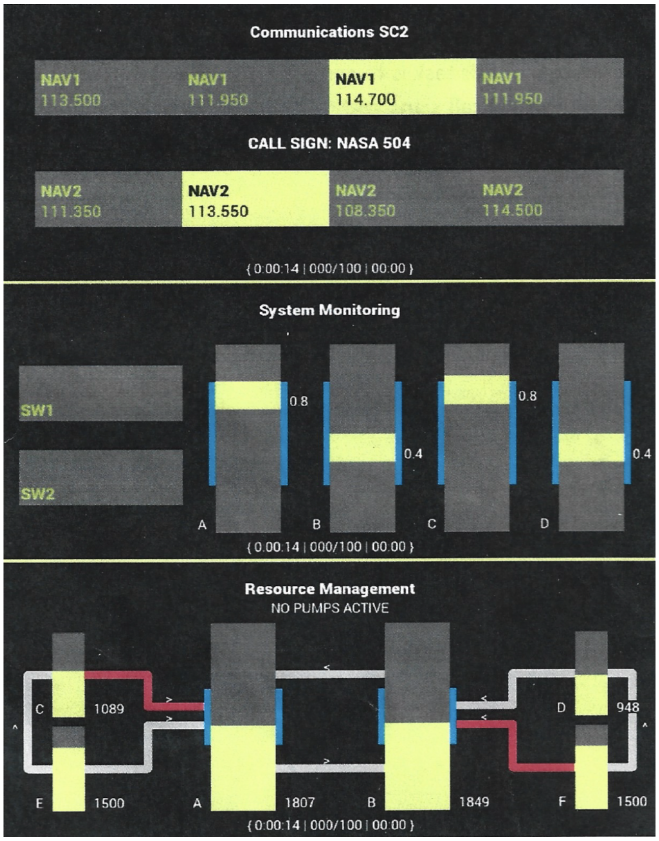
HR was then used to calculate Heart Rate Reserve ($\%HRR = (HR_{exercise} – HR_{rest}) / (HR_{max} – HR_{rest})$), which is an established method of estimating or prescribing exercise intensity (Mann et al., 2013). Compared to absolute intensity measurements such as stage or duration of the graded exercise task, treadmill speed, etc., %HRR allows exercise intensity to be measured relative to the individual. This accounts for potential differences in overall fitness level and time to exhaustion (i.e., one participant might reach 90% HRR in stage 7, while another might reach 90% HRR in stage 10). %HRR served as the present study's primary measure for exercise intensity.

Cognitive Assessment

The Cedar Operator Workload Assessment Tool (OWAT; elmTEK, Australia). The OWAT is a tablet-based adaptation of the NASA Multi-Attribute Task Battery-II (MATB–II) used to evaluate cognition. The OWAT is completed on an iPad and employs a multitasking model to assess domains of executive function such as decision-making, working memory, and sustained attention. While the tasks administered by the OWAT and MATB-II were initially developed to simulate those relevant to flight crews, the paradigm has proven suitable for civilian populations (Cegarra et al., 2020; Comstock & Arnegard, 1992).

Figure 2

The OWAT



The OWAT requires participants to simultaneously perform communications, systems monitoring, and resource management tasks (Figure 2). The communications task is designed to simulate tactical transmissions. A series of speakers provide one of several possible call signs, accompanied by instructions to turn a specific radio channel to a specific frequency. The participant is assigned a call sign, “NASA 504”, before the initiation of the task and instructed only to respond when they hear their call sign. In the systems monitoring task, participants are asked to attend to warning bars and a set of scales with fluctuating bars. Participants respond by tapping the bars when they turn red. The task presented on the final 1/3 of the iPad screen is resource management, which involves monitoring a set of fuel tanks and ensuring that they stay filled to a certain level; as the levels drop, the participant must open or close valves shown on the screen (by tapping them) to send fuel from one of the supply tanks into the main tanks.

The OWAT is better suited to evaluate executive function continuously across exercise intensity than many available task batteries, as the OWAT is not divided into individual tasks presented one after another. Because the OWAT is comprised of three tasks performed concurrently, it allows multiple facets of executive function to be measured simultaneously across the exercise duration. This is in contrast to task batteries such as CANTAB or ANAM, whose tasks are typically shorter in duration and presented sequentially. Given that the demands on cognition will increase across exercise intensity, serially ordered task performance would be biased by what point each task is encountered during the graded exercise task. Likewise, many available task batteries are validated for use over certain, often short, time durations. The design of the OWAT tasks allows for sustained measurement of executive function across longer time spans than many readily available testing paradigms. As such, the OWAT is particularly well-suited for the present investigation.

The OWAT provides two global measures of executive function, hit rate and precision, both of which will be included in the analyses as dependent variables. The hit rate is the number of correct ‘hits’ divided by the total number of responses (hits + false positives + misses).

Precision is defined as the number of correct hits divided by total hits (hit + false positives).

Procedure

Those who were interested began by completing the online screening and questionnaire battery via Qualtrics (Qualtrics, Provo, UT). Screening responses were reviewed to identify potential health conditions that would preclude participants from completing the exercise portion of the study. Those eligible to participate further were invited to the lab to complete two in-person visits. When scheduling the in-person visits, participants were provided with a description of study protocols and asked to refrain from vigorously exercising 24 hours before their visits and consuming caffeinated beverages before participation. Participants were also instructed to wear comfortable exercise clothing and close-toed shoes suitable for treadmill training.

Visit one involved task familiarization and maximal graded exercise testing (GXT). Research staff began the initial visit by reviewing the informed consent document with participants, who were given the opportunity to ask questions and take as much time as needed to consider before signing. The same procedure was followed for the completion of the HIPPA form. From there, female participants were required to undergo a pregnancy test as an IRB-stipulated prerequisite for study eligibility in an effort to prevent those who might unknowingly be pregnant from experiencing undue risks as a result of participation.

Following the completion of paperwork and prerequisite testing, research staff provided a verbal overview of the OWAT, including specific instructions for each task. Written and standardized instructions were then provided for participants to read. After providing an opportunity to ask questions and clarify any aspects of the tasks that were still unclear, participants were given two 8-minute opportunities to practice the task, with 10 minutes intervening between practice sessions. Extant research has demonstrated that improvements due to task familiarity for some higher-order cognitive tasks are typically completely attenuated following two test administrations sessions separated by as little as 10 minutes (i.e., no further learning effects are seen following the second administrations; Collie et al., 2003; Falleti et al., 2006; Goldberg et al., 2015), and the training/practice performance blocks were selected to ensure that performance reached asymptotic levels prior to the initiation of the combined exercise and cognitive task to avoid learning effects (Schlegel & Gilliland, 1990).

After completing the OWAT practice, participants were outfitted with physiological monitors and familiarized with the procedures for completing the treadmill GXT, including instructions for signaling volitional exhaustion and safely exiting the treadmill. At the outset of the task, participants were instructed to stand still and quietly on the treadmill for 2 minutes to obtain baseline measurements. After the baseline period, research staff provided a "3, 2, 1, go" countdown and the treadmill speed was set to 3.5 mph at a 0% incline (Nelson et al., 2009). The inline was then increased by 2% every 2 minutes until a grade of 16% was reached; if participants completed 2 minutes at a 16% incline, the speed was then increased by 0.5 mph for the remaining duration of the test (Nelson et al., 2009). Research staff encouraged participants to continue the test for as long as safely possible but reminded them prior to the baseline period that they could end the test at any point.

When ready to signal volitional exhaustion and the end of the test, participants placed their hands on the treadmill railing and carefully moved their feet off the belt. At this point, a researcher stationed at the head of the treadmill brought the incline down to 0% and the speed to 2.0 (or lower, as required by participant tolerance) to allow participants to complete a 2-minute cooldown period. Upon completion of the GXT, participants were thanked for participating, and their appointment for Visit 2 was confirmed.

Visit 2 was scheduled for at least 24 hours, no more than two weeks intervening, and involved a combined exercise and cognitive test. While the same procedures for the exercise portion of Visit 2 remained the same, the iPad loaded with the OWAT task was affixed to the front of the treadmill to allow participants to complete the OWAT concurrently throughout exercise. When the participant signaled exhaustion, a researcher stationed at the head of the treadmill ended the OWAT task. At the conclusion of the cooldown period, participants were allowed to rest as long as needed and thanked for their participation.

Results

Statistical Analyses

Data cleaning, compiling, and statistical analyses were completed using a combination of SAS OnDemand for Academics (SAS Institute, 2024) and RStudio (Posit Software, 2023).

Repeated measures general linear models (RMGLMs) were used to assess primary and secondary study hypotheses relating to the relationship between pain catastrophizing, exercise intensity, and cognitive performance. While this question could also have been analyzed using a repeated measures analysis of variance, the GLM allows for less “loss” of information and variability by using individual’s scores on the PCS within the model instead of “binned” categories of “low” and “high” and greater statistical power. Observations were nested by subject ID to account for the repeated measures nature of the data, with the precise mathematical representations of the models listed below. RMGLMs were then repeated with values below 50% HRR eliminated and compared with model results including data from baseline to 100% HRR in order to ensure initial variability or outliers in cognitive performance, likely observed due to the adjustment period for responding to the task on the treadmill, did not artificially skew results or result in falsely positives.

Figure 3.

Mathematical representations of RMGLMs.

$$\text{Hit Rate}_{ij} = \beta_0 + \beta_1\text{HRR}_{ij} + \beta_2\text{PCS score}_{ij} + \beta_3(\text{HRR}\times\text{PCS score})_{ij} + u_{0j} + \epsilon_{ij}$$

$$\text{Precision}_{ij} = \beta_0 + \beta_1\text{HRR}_{ij} + \beta_2\text{PCS score}_{ij} + \beta_3(\text{HRR}\times\text{PCS score})_{ij} + u_{0j} + \epsilon_{ij}$$

In order to ensure test assumptions were met prior to final analyses, variable residuals were plotted and visually expected for normality. Total error for the study was set to $p < 0.05$ and controlled using Bonferroni adjustments.

Descriptive Statistics

A total of 28 healthy students aged 18-35 from the University of Oklahoma (Norman, Tulsa, and Health Sciences Center campuses) accepted invitations to complete the in-person portion of the study following the initial screening and online collection through Qualtrics. All 28 students consented to participate in-person and completed both required visits (i.e., no loss to follow-up between Visit 1 and Visit 2). One participant's data was excluded from analysis due to significant anomalies 1) in baseline heart rate data from Visit 1 to Visit 2, and 2) in cognitive task scores during the first 6 minutes of the combined task. As such, data from 27 participants were included in the final analysis, as required to achieve 80% power. Demographic data are reported in Table 1 with values reported as mean±SD or frequency.

Table 1

Demographic and Summary Statistics

	mean+SD
Age (years)	23±6
Pain Catastrophizing Score	5.8±7.8
Duration of Exercise-Visit 1 (seconds)	1217.8±324.5
Duration of Exercise-Visit 2 (seconds)	1212.7±315.5
	frequency
Sex	
Male	14 (52%)
Female	13(48%)
Race	
White, non-Hispanic	19(70%)
Black or African-American	3(11%)
Hispanic or Latino	3(11%)
Asian	1(4%)
American Indian or Alaska Native	1(4%)

RMGLMs

It was hypothesized that increases in exercise intensity would be associated with decrements in cognitive performance, measured as hit rate (correct hits / hits + false positives + misses) and precision (correct hits / hit + false positives), and that pain catastrophizing would moderate that relationship. As expected based on previous findings, relative exercise intensity measured as HRR had a significant main effect on both Hit Rate (β = -0.0619, SE = 0.00238, t = -26.49, p < 0.0001) and Precision (β = -0.0530, SE = 0.00145, t = -36.555, p < 0.0001), with both cognitive indices declining as relative exercise intensity increased (Table 2). Based on the coefficients associated with the models' fixed effects, hit rate decreases by 0.2085%, while precision decreases by -0.0837% for every one unit increase in heart rate reserve.

Table 2

RMGLM Results

$\text{Hit Rate}_{ij} = \beta_0 + \beta_1\text{HRR}_{ij} + \beta_2\text{PCS score}_{ij} + \beta_3(\text{HRR}\times\text{PCS score})_{ij} + u_{0j} + \epsilon$	β	t-value	Pr(>|t|)	
HRR	-6.29E-02	-26.492	< 2e-16	***
PC score	2.82E-03	1.676	0.106	
HRR*PC score	-1.90E-03	-7.386	1.65E-13	***

$\text{Precision}_{ij} = \beta_0 + \beta_1\text{HRR}_{ij} + \beta_2\text{PCS score}_{ij} + \beta_3(\text{HRR}\times\text{PCS score})_{ij} + u_{0j} + \epsilon_{ij}$	β	t-value	Pr(>|t|)	
HRR	-5.30E-02	-36.555	< 2e-16	***
PC score	-6.95E-04	-1.182	0.247633	
HRR*PC score	5.63E-04	3.582	3.43E-04	***

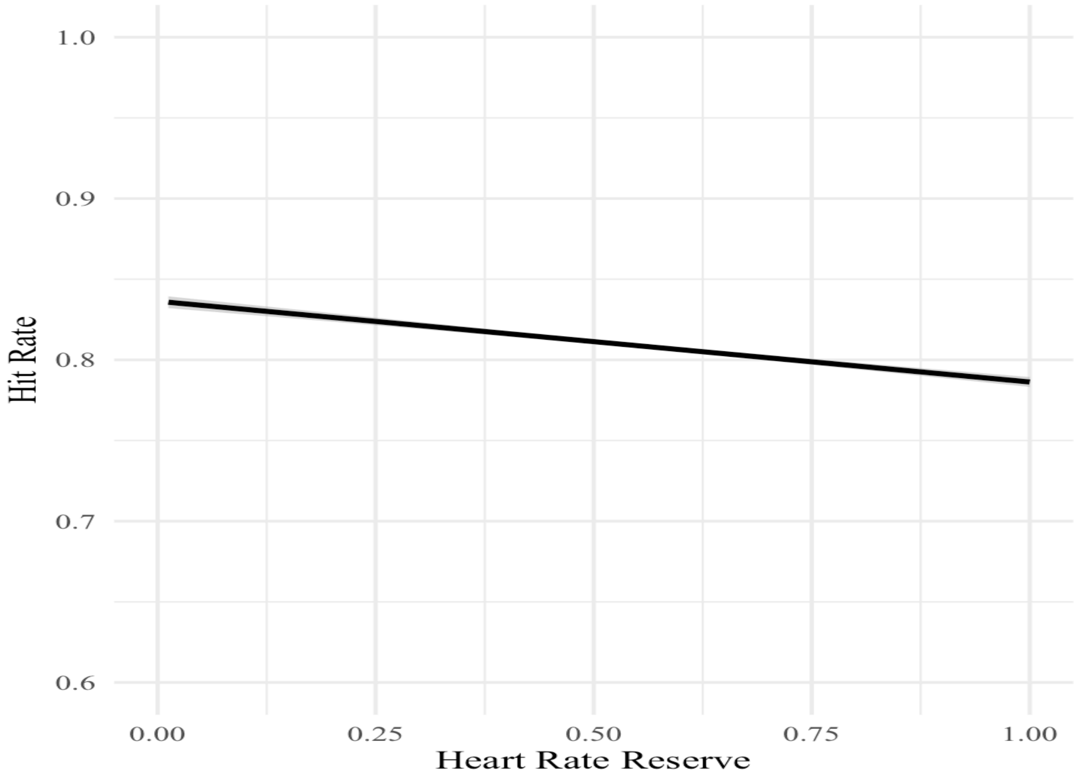
***p < 0.001

Independently, pain catastrophizing did not have a significant main effect on hit rate (β = 0.00282, t = 1.676, p = 0.106) or precision (β = -0.000659, t = -1.182, p = 0.248; Figure 4;

Appendix A). However, pain catastrophizing did moderate the relationship between exercise intensity and both hit rate (β = -0.00190, p < .0001; Figure 3&4) and precision (β = 0.000563, p < .001; Figure 5, Appendix B), with highly significant t-values of -7.386 and 3.582 respectively. This suggests both that the extent to which exercise intensity impacts cognition varies based on the degree of pain catastrophizing, and that pain catastrophizing has a complex, multidirectional impact on cognitive indices via improvements in positive predictions (i.e. fewer false positives, greater precision) and declines in overall accuracy (i.e. missing more true positives, lower hit rate). This partially supports the primary study hypothesis but potentially indicates a more complex relationship between pain catastrophizing and cognition than originally hypothesized. These results are summarized in Table 2.

Figure 4

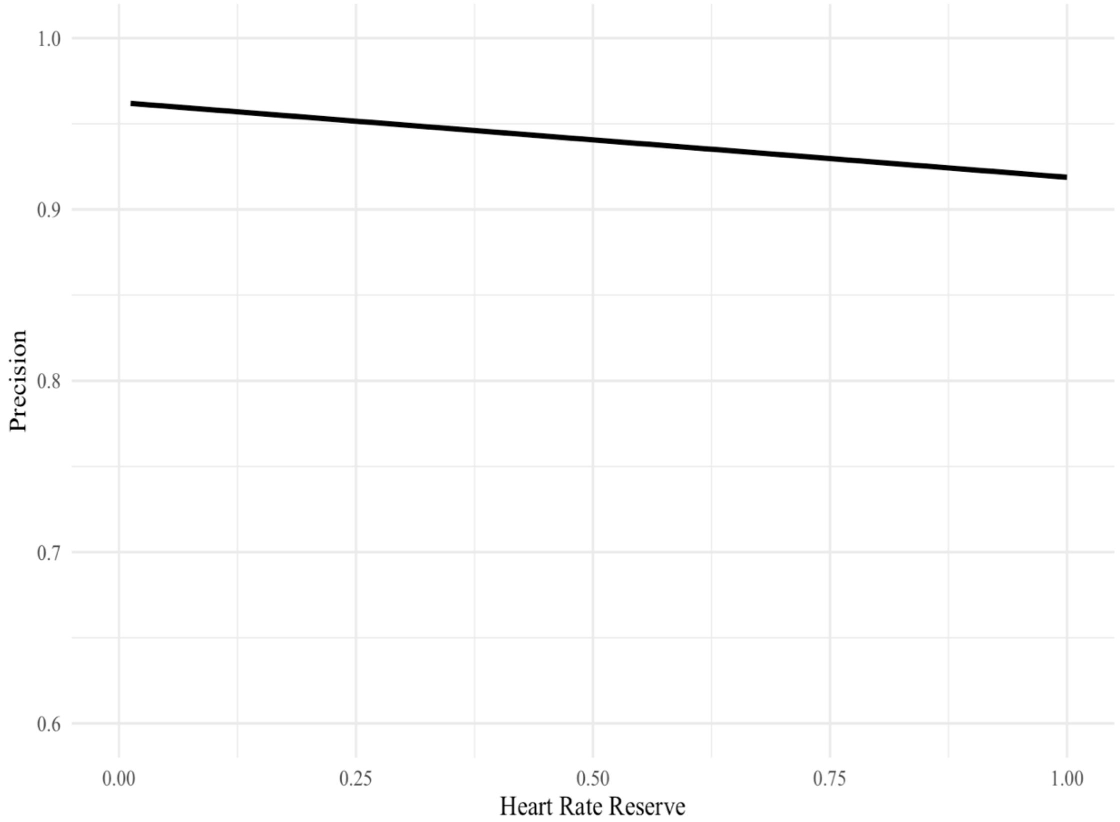
The Impact of Exercise Intensity (Heart Rate Reserve) on Hit Rate: Aggregate



Note: demonstrates the regression line for the relationship between exercise intensity, measured as heart rate reserve, and cognitive performance, measured as hit rate.

Figure 5

The Impact of Exercise Intensity (Heart Rate Reserve) on Precision: Aggregate



Note: demonstrates the regression line for the relationship between exercise intensity, measured as heart rate reserve, and cognitive performance, measured as precision.

Increased variability in cognitive task performance during the initial stages of exercise was apparent for a number of participants (see Appendix A and B for individual data plots). Although some degree of variation in performance is expected initially as participants adjust to the challenge of responding to the task on the treadmill, in an effort to ensure this additional "noise" in the data did not unduly skew the trend line, the analyses were repeated with data from 50% heart rate reserve and above. The main effect of HRR and modifying effect of pain catastrophizing remained highly significant for both cognitive indices (Table 3), with relatively small deviations in values or significance levels (Table 3). This indicates that the heightened levels of variability on the cognitive performance task in the initial stages of exercise, which appeared to be due primarily to participant's adjusting to responding to the task while moving on the treadmill, did not significantly impact the study results.

Table 3

RMGLM Results: 50% HRR and Above

$\text{Hit Rate}_{ij} = \beta_0 + \beta_1\text{HRR}_{ij} + \beta_2\text{PCS score}_{ij} + \beta_3(\text{HRR}\times\text{PCS score})_{ij} + u_{0j}$	β	t-value	Pr(>|t|)	
HRR	-6.72E-02	-25.902	< 2e-16	***
PC score	2.79E-03	1.673	0.106	
HRR*PC score	-1.96E-03	-6.639	3.4E-11	***

$\text{Precision}_{ij} = \beta_0 + \beta_1\text{HRR}_{ij} + \beta_2\text{PCS score}_{ij} + \beta_3(\text{HRR}\times\text{PCS score})_{ij} + u_{0j} +$	β	t-value	Pr(>|t|)	
HRR	-5.30E-02	-36.555	< 2e-16	***
PC score	-6.95E-04	-1.182	0.247633	
HRR*PC score	5.00E-04	2.860	0.004	**

***$p < 0.001$; **$p < 0.01$

Secondary Analyses

In order to further describe and evaluate secondary study variables, a series of t-tests and correlation matrices were completed. A paired sample t-test revealed no significant differences in length of exercise between Visit 1 and Visit 2 ($t(26) = 0.27$, $p = .786$). Similarly, while there is some extant evidence to suggest increased likelihood of PC in females, an independent t-test calculated to assess gender differences in indicated no differences in PC score (t(20.07) = 1.44, p = .166) between men and women in the present study. These results are summarized in Table 3.

Table 3

T-Tests for Secondary Variables

One Sample Paired T-Test	Length of Visit (mean+SD)	t-value	Pr(>|t|)	CI
Length of Visit		0.274	0.786	-32.96, 43.11
Visit 1	1217.8±324.5			
Visit 2	1212.7±315.5			
Two Sample T-Test	**PC Score (mean+SD)**	**t-value**	**Pr(>|t|)**	
Gender		1.437	0.166	-1.93, 10.51
Female	8±9.17			
Male	3.714±5.82			

Spearman's correlation coefficients for secondary study variables are reported in Table 4. Consistent with existing literature, measures of heart rate were significantly associated with duration of exercise. Pain catastrophizing, however, was not correlated with resting heart rate, maximal heart rate, or duration of exercise for Visit 1 or Visit 2.

Table 4

Correlation Matrix for Secondary Variables

Correlation and P-Value Matrix					
	Resting Heart Rate	Max Heart Rate	Exercise Length (Visit 1)	Exercise Length (Visit 2)	PC Score
Resting Heart Rate		rho = 0.472	rho = -0.505	rho = -0.525	rho = 0.054
Max Heart Rate	p = 0.013**		rho =- 0.160	rho = -0.174	rho = 0.229
Exercise Length (V1)	p = 0.007**	p = 0.426		rho = 0.955	rho = -0.018
Exercise Length (V2)	p = 0.005**	p = 0.387	p <0 .001**		rho = -0.032
PC Score	p = 0.790	p = 0.250	p = 0.930	p = 0.872	

Discussion

The present study proposed to evaluate the impact of pain catastrophizing on the relationship between executive function and exercise intensity. The primary expectations were that cognitive performance would be attenuated at high levels of exercise intensity, and that these attenuations would be moderated by pain catastrophizing. Specifically, the present study hypothesized both that increases in heart rate reserve would be associated with decreases in the executive function performance, as measured by hit rate and precision, and that higher levels of pain catastrophizing would result in more significant decrements performance on both cognitive indices.

Exercise Intensity and Cognition: Reinforcing What We Know

In line with results from Stone et al. (2020), hit rate and precision decreased linearly with increases in exercise intensity. As only the second examination of cognitive performance continuously across exercise from baseline to maximal levels, this study serves to further underscore the robustness of the relationship between exercise intensity and concurrent cognitive decline and to support the numerous other studies demonstrating concomitant decrements in cognition during high intensity exercise (Dietrich & Sparling, 2004; Komiyama et al., 2019; McMorris et al., 2009; Smith et al., 2016; Stone et al., 2020; Wang et al., 2013). Although these results contrast with those of Lucas et al. (2012), Schmit et al. (2015), and Dowdell et al. (2019), differences in experimental paradigms enumerated in other sections, particularly final intensity level reached (Dowdell, 2019) and total duration of exercise (Lucas et al. 2012; Schmit et al. 2015), are proposed to explain these variations.

Pain Catastrophizing: A Complex Modifier of Cognition During Exercise

In addition to replicating the findings of Stone et al. (2020), the present study served as the first to experimentally explore the relationship between exercise, cognition, and pain catastrophizing. Importantly, this investigation provides preliminary support for the hypothesis that the relationship between exercise intensity and cognitive performance during exercise is modified by pain catastrophizing levels. Specifically, higher pain catastrophizing levels were predictive of greater decrements in hit rate, but higher levels of precision, across exercise intensity. Although the results suggest a more nuanced relationship than originally anticipated, these findings are theoretically sound when considering models of attention and resource allocation.

High intensity exercise (Dietrich & Audiffren, 2011) and the utilization of executive function (Gailliot, 2008; Tomasi, Wang, & Volkow, 2013) are both metabolically expensive tasks. The body operates utilizing a finite amount of neural resources (Attwell & Laughlin, 2001; Bruckmaier et al., 2020; Lennie, 2003), and extant research supports the idea that the tradeoffs between the mental resources required to sustain exercise underlie the declines in cognition seen at high exercise intensities (Dietrich & Audiffren, 2011; Stone et al., 2020). Considering individuals high in pain catastrophizing are more likely to expend a disproportionate amount of mental resources attending to pain related stimuli (Spanos et al., 1979; Chaves and Brown, 1987; Eccleston et al., 1999; Van Damme et al, 2002 & 2004; Van Cleef et al. 2006 Michael et. al 2004, Quartana et al., 2009; Sillican, 1995), and that the mental resources devoted to pain perception will likely increase as exercise intensity-related discomfort increases (Lier et al, 2022; Wagennar-Tison et al., 2022), it is logical to conclude that individuals higher in pain catastrophizing would experience higher levels of cognitive load, and thus further depletion of mental resources, than their non-catastrophizing counterparts.

While more complex than originally supposed, the results of the present study support the conclusion that higher levels of pain catastrophizing may result in decreased capacity to attend to a cognitive task during high intensity exercise. Individuals high in pain catastrophizing were more likely to exhibit fewer false positives as exercise intensity increased, but they were also more likely to miss true positives. When considering this result in the context of previously discussed resource allocation theories, it is reasonable to suppose that those high in pain catastrophizing might have fewer false positives as exercise intensity increased because they were generally attending to the task less; this supposition is particularly logical given the present evidence that those individuals had a concomitant, global increase in the total number of missed responses. Given that increases in exercise intensity appear to predispose individuals higher in pain catastrophizing to 1) responding less to the task overall, and 2) committing more errors when they do respond, it is reasonable to conclude that aberrations in capacity to maintain attention to the task may be contributing to the complex effects on executive function performance.

In general, these findings align with those of other works demonstrating that individuals higher in pain catastrophizing are less able to disengage with pain-related stimuli in order to maintain attention on other tasks (Crombez et al., 2002; Eccleston & Crombez, 1999; Lee et al., 2018; Legrain, Perchet, et al., 2009). Although the present study did not include functional imaging or measurements of cerebral blood flow, deviations in responsiveness to the task could be explained by previously demonstrated aberrations in top-down processing mediated by decreases in activity in areas such as the DLPF and increased activity in areas associated with affective processing of painful stimuli, such as the ACC. By and large, the present investigation demonstrates a novel interaction of pain catastrophizing on the relationship between cognition and exercise while also providing support for the attentional-model of pain catastrophizing.

Limitations and Future Directions

Given that this is the first study to look specifically at the impact of pain catastrophizing on the relationship between exercise intensity and cognition, additional research must be conducted to confirm these findings, further assess the conditions under which pain catastrophizing serves as a significant moderator, particularly in relation to the demonstrated differences in precision and hit rate, and provide additional insight into the mechanisms underlying the presumed degradations in attention, particularly in regard to the biological mechanisms proposed in the previous section to explain the effects observed in this investigation.

For example, while preliminary inspection did not reveal significant baseline differences in performance on the cognitive task by pain catastrophizing score in the present study, it is important to consider that the increased variability in individual participant's task performance in the initial stages of the exercise task may have masked pre-existing, pain-catastrophizing-related discrepancies in executive function. With this in mind, an additional cognitive task training period on the treadmill may have served to provide a comparison period by which stronger conclusions could be made regarding the degree to which the discomfort of exercise versus a generally lower ability to maintain attention, regardless of the nature of the stimuli, accounted for the observed subsequent decrements in cognition. Although there is a wealth of evidence to indicate that individuals with higher levels of pain catastrophizing exhibit attentional biases toward pain-related stimuli specifically, further exploring whether pain catastrophizing is associated with lower levels of overall cognitive reserve in non-clinical samples may provide additional insight into the mechanisms underlying the patterns identified in the present study. All in all, the inability to confidently tease out potential differences in executive function by pain catastrophizing at baseline in the present investigation is a limitation that should be addressed in future studies.

Likewise, while self-reported levels of pain during exercise were not assessed in an effort to avoid priming participants to thinking about the level of discomfort they were experiencing as intensity increased, this work could have benefitted from collecting information related to the subjective pain-related experiences of participants as they were on the treadmill. Although it is generally accepted that intense exercise is accompanied by discomfort (Mauger, 2019; O'Malley et al., 2024), with exercise being considered an accepted method of experimentally inducing pain (Edens & Gil, 1995; Reddy et al., 2012), information related to the extent and timing of discomfort would have allowed for additional clarity on the extent to which pain-related cognitions or greater focus on pain-related stimuli were impeding ability to attend to the cognitive task. Ratings of perceived exertion, typically assessed with the Borg scale, are often employed in exercise science investigations in order to assess the level of pain without specifically using that term (O'Malley et al., 2024), particularly in populations prone to reporting pain-related symptoms during exercise, such as those with Gulf War Syndrome (Cook et al., 2010). However, given the hypervigilance exhibited by individuals who are higher in pain catastrophizing to stimuli that could potentially signal pain, even in the presence of neutral rather than painful stimuli (Khatibi et al., 2015), asking catastrophizers to consider their level of exertion might unduly influence them to attend even further to the discomfort they might be experiencing or anticipating experiencing. This concern has been similarly raised in populations with fibromyalgia, with conflicting evidence exists as to whether patients are able to effectively discriminate between exertion and exercise-induced pain (Nielens et al., 2000; Soriano-

Maldonado et al., 2015). While these constraints make it challenging to concurrently assess the degree to which pain catastrophizing impacts the experience of discomfort during exercise without priming pain-related cognitions, future studies should endeavor to more clearly explore this relationship, perhaps using qualitative methods administered immediately post-exercise.

It is also important to consider that the participants included in the present study were young, healthy, and interested in taking part in a study that required maximal exercise. When considering additional study limitations, it is possible that these factors influenced their response to exercise, the degree of cognitive decline experienced and reported levels of pain catastrophizing. Similarly, many of the participants were enrolled in allied health programs, and those individuals likely had some familiarity with the concept of pain catastrophizing; those who did might have been less likely to respond in the affirmative to questions on the Pain Catastrophizing Scale.

Furthermore, while the range of pain catastrophizing scores in the present sample mirrors those of other studies utilizing pain-free participants (e.g. Asefi Rad & Wippert, 2024), it is important to consider that the present sample might not adequately reflect the degree of decline that might be seen in those with clinically high levels of pain catastrophizing. As previously mentioned, pain catastrophizing has been commonly evaluated in clinical samples given its well-demonstrated predictive value, but it is considered to be “universally observed” across populations (Ikemoto et al., 2020; Simic et al., 2024). While assessing pain catastrophizing in non-clinical samples is both appropriate, given evidence that catastrophizing is present in healthy populations and can manifest at a relatively young age and without exposure to significant painful experiences (Sullivan et al., 2001; Turk & Okifuji, 2002), and necessary in order to fully conceptualize the construct, it is important to be cautious about making generalizations between samples with and without pain-related conditions. In this vein, although the PCS has typically been utilized to assess dispositional pain catastrophizing, a recent investigation by Day (2021) has suggested that while the scale does primarily assess dispositional catastrophizing in healthy samples, aspects of both dispositional and situational catastrophizing are likely captured by the PCS in patients with chronic pain. This lends further support to the appropriateness of the use of the PCS in the present investigation and highlights the value of further exploring potential variations in dispositional versus situational catastrophizing on relationship of exercise, cognition, both in terms of validity of measurement and impacts on performance, in both healthy and clinical samples . All in all, additional research should be conducted in populations for whom pain catastrophizing is present at a higher rate, such as those with a history of pain, injury, or illness.

In addition to assessing state versus trait characteristics of catastrophizing in future investigations, assessing the relationship of catastrophizing to individual differences typically considered to be traits might also provide more nuanced insight into when the attentional deficits observed in the present study might be most salient. Although outside the scope of the present investigation, exploration of how personality traits might further exacerbate or attenuate the impact of pain catastrophizing on cognition during exercise could shed light on findings in the present study related to higher false positive rates early in exercise, followed by steep declines in general response rate and accuracy of response. For example, pain catastrophizing has been most commonly associated with neuroticism, a dimension that shares some features with pain catastrophizing, including a general hypervigilance to negative stimuli, a greater tendency to experience negative emotions, and a heightened tendency to overemphasize bodily sensations (Watson & Pennebaker, 1989). Individuals reporting higher levels of neuroticism are more likely to endorse high levels of pain catastrophizing (Atanassova et al., 2024; Burri et al., 2018; Kadimpati et al., 2015), but it is important to note that despite both constructs being related to fear of and enhanced vigilance, pain catastrophizing has been demonstrated to uniquely contribute to the pain experience, with the degree to which neuroticism impacts vigilance to pain-specific stimuli actually being dependent on level of pain catastrophizing (Goubert et al., 2004). Similarly, Burri and colleaugues (2018) provided compelling evidence that genetic overlap between pain catastrophizing and neuroticism is relatively low. However, this relationship is still important to consider moving forward, particularly in regard to assessing the extent to which catastrophizing versus neuroticism account for observed attentional deviations during cognitive and exercise performance.

Given that these findings have potentially important implications for performance optimization, future work should also endeavor to assess the relationship of exercise, cognition, and pain catastrophizing in applied samples for which 1) the ability to maintain high levels of executive function and intense physical output concurrently are crucial to safety or to mission or on-the-job success, or 2) the application of dual-task paradigms might be particularly beneficial for rehabilitative purposes.

In general, given the demonstrated decreases in overall accuracy and tendency to miss relevant stimuli in the present study, better understanding how pain catastrophizing might impact signal detection in settings in which alerting to relevant stimuli may be of the upmost importance is crucial (Vrijkotte et al., 2016). In addition to confirming the findings of the present study in these populations, specifically that pain catastrophizing exacerbates decrements in accuracy in responses on cognitive tasks during exercise when assessing more mission-specific or on-the-job paradigms, it will also be important to continue to more generally assess the conditions under which the impacts of exercise and pain catastrophizing might interact to impact methods of performance optimization. For example, when considering studies in safety sensitive groups demonstrating evidence that Army Combat Fitness Test Scores moderate enhancements in cognition post-ruck (Sax van der Weyden et al., 2022) and that lower cardiovascular fitness level are proposed to dampen the benefits of acute exercise on BDNF levels post-exercise in healthy college students (Muñoz Ospina & Cadavid-Ruiz, 2024), it seems reasonable to posit that pain catastrophizing may also blunt the degree of cognitive enhancement and potential neuroendocrine benefits reported following the cessation of exercise (Moreau and Chou, 2019). In addition to assessing the possibility of pain catastrophizing exacerbating acute decrements in cognition during exercise in these populations, it may also be beneficial to explore whether higher levels of pain catastrophizing reduce the benefits of exercise on cognition—or on other important performance and physiological metrics—in these populations.

While the potential consequences of exercise-induced cognitive alterations are perhaps more apparent in safety sensitive occupations, there are also potentially significant ramifications in athletic and therapeutic settings. Extant research indicates that individuals high in pain catastrophizing are more likely to have poorer outcomes following orthopedic surgical procedures and are more likely to respond poorly to physical therapy or other forms of rehabilitation. This may be of increased concern in athletic populations, for whom recovery and return-to-sport may represent a crucial component of identity or livelihood. Return-to-sport rehabilitation protocols for athletes often utilize dual-task paradigms, in which the athlete is required to complete a sport-specific movement while also undergoing some sort of cognitive challenge. Given that intensity of rehabilitation is an essential driver of adaptive change in physical rehabilitation, interactions between pain catastrophizing and the physical and cognitive challenge demonstrated in the present study could explain in part why many individuals respond more poorly to dual-task therapeutic interventions for chronic pain (Martinez-Calderon et al., 2020) or return-to-sport (Browning et al., 2021). With this in mind, future paradigms should address this interplay more fully.

Similarly, while pain catastrophizing has been shown to impact a broad range of pain-related outcomes, as well as the likelihood and degree of disability following acute or chronic injury in safety-sensitive and sport settings, much less focus has been placed on actual work or sport-related performance (Ciccone & Kline, 2012; Judkins et al., 2022; Mollow et al., 2020, Schaaf et al., 2023; Spevak & Buckenmaier, 2011; Paparizos et al., 2005; Sciascia, Waldecker, Jacobs, 2020; Sullivan et al., 2000; Tripp et al., 2007). For example, Paparizos and colleagues (2005) examined the relationship between the experience of pain and pain catastrophizing in a population of ballet dancers, but no assessments of sport-related performance were made. Similarly, while Gagnon-Dolbec, Fortier, and Cormier (2021) demonstrated a significant correlation between higher reported levels of pain intensity and pain unpleasantness in triathletes with higher pain catastrophizing scores, studies geared toward assessing how these relationships influence athletes performance would be of immense value.

Future research should also address the efficacy of interventions for pain catastrophizing on the improvement of cognition during exercise. There are a number of well-studied interventions for reducing pain catastrophizing in adults with chronic pain (Schütze et al., 2018), and the application of pre- and post-catastrophizing intervention assessments of the impact of exercise on cognition would serve to potentially provide additional support for the causal basis for the role of pain catastrophizing on cognitive decline during exercise, as well as to identify targeted interventions to limit demonstrated decrements. In the context of applied settings, reductions in high baseline levels of pain catastrophizing via a course of specialty pain care was associated with lower levels of medical disability at a later date in military personnel, indicating that pre-deployment education may impact future functional outcomes (Schaaf et al., 2023); this avenue should also be explored more fully, particularly in relation to how the interventions impact the performance of job-related requirements.

Conclusions

Numerous investigations have demonstrated declines in executive function during high-intensity exercise. Overall, this study confirms previous findings and provides preliminary evidence that pain catastrophizing might further alter cognitive performance during exercise at high intensities. This knowledge is particularly relevant in contexts such as safety-sensitive occupation, athletic training, and rehabilitative sciences where optimal cognitive function is essential for decision-making, performance, and overall well-being. Given the novelty of the investigation and the potential implications of the findings for a variety of settings in which performance optimization is the goal, this relationship deserves continued attention.

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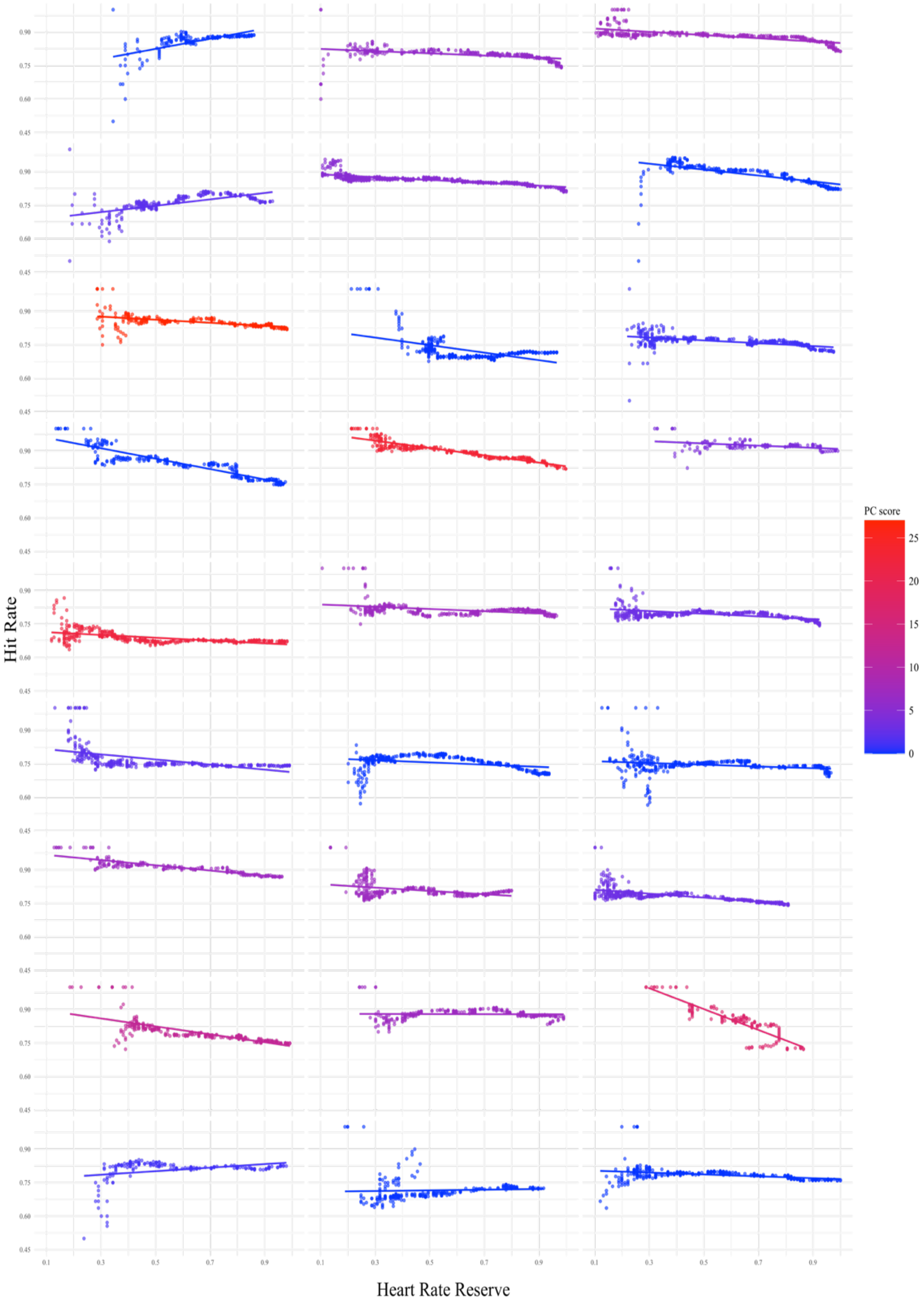
Appendix A

The Impact of Exercise Intensity (Heart Rate Reserve) on Hit Rate: Individual Plots



Appendix B

The Impact of Exercise Intensity (Heart Rate Reserve) on Precision: Individual Plots