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Characterizing the Relationship Between Objective Physical Activity and Momentary Pain in Cognitive Behavioral Interventions for Chronic Pain

A dissertation submitted in partial satisfaction of the
requirements for the degree Doctor of Philosophy

in

Clinical Psychology

by

Mara Tynan

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2026

The dissertation of Mara Tynan is approved, and it is acceptable in quality and form for publication on microfilm and electronically.

Chair

University of California San Diego
San Diego State University

2026

DEDICATION

To my family, for raising me to value education and question everything.

To my friends, for believing in me more than I believe in myself.

To my mentors, for your high standards and giving your time and expertise selflessly.

To my athletic endeavors, for helping me keep perspective, make new friends, and see the world.

To Mateo, for keeping me laughing, fed, and just the right amount of distracted.

To my cat Boo, you are kind of a pain, but I love you.

And finally, to everyone who asked, “You’re *still* working on that?”—Yes. Yes, I was.

EPIGRAPH

"This'll be fun!"

- Me, approximately 5 years ago, age 25.

"Maybe running a marathon will make this feel easier."

- Me, approximately 3 years ago, age 27.

"Getting a kitten will surely make things better."

- Me, approximately 2 years ago, age 28.

"Going to Sweden for Ötillö the Swimrun World Championship will definitely lighten the load."

- Me, approximately 1 year ago, age 28.

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LIST OF ABBREVIATIONS

Acceptance and Commitment Therapy (ACT)

ACTing with Mindfulness for Pain (AMP)

Cognitive Behavioral Therapy (CBT)

Ecological Momentary Assessment (EMA)

Latent Growth Curve Model (LGCM)

Post-Traumatic Stress Disorder (PTSD)

Robust Maximum Likelihood Estimation (MLR)

Structural Equation Modeling (SEM)

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FIELDS OF STUDY

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Professor Matthew S. Herbert

ABSTRACT OF THE DISSERTATION

Characterizing the Relationship Between Objective Physical Activity and Momentary Pain in Cognitive Behavioral Interventions for Chronic Pain

by

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University of California San Diego, 2026
San Diego State University, 2026

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Chronic pain, a disabling biopsychosocial condition, is increasingly addressed with cognitive behavioral interventions such as Acceptance and Commitment Therapy (ACT) and Cognitive Behavioral Therapy (CBT). Such interventions seek to maximize physical, social, and occupational functioning by changing how one manages pain via addressing pain-related thoughts, beliefs, and behaviors. The chronic pain literature is dominated by between-subject designs and self-report measures that lack ecological validity and may be subject to bias. Both pain and physical activity, a component of function, can be objectively measured in an ecologically valid way using ecological momentary assessment (EMA) and accelerometry, respectively. Prior research has indicated cross-sectionally a dynamic within-person pain-physical activity relationship, but statistical analytic approaches have lacked nuance, and this relationship has not been examined in an intervention context. This dissertation addressed gaps in the literature by 1) modelling the relationship between EMA-assessed pain and objective physical activity over a 7-day baseline period using parallel latent growth curve modelling; 2) using multigroup analysis to examine if the relationship between the growth trajectories of EMA pain and objective physical activity changed from baseline to post-intervention, and 3) qualitatively exploring how treatment impacts individuals' *function* while having pain. These aims were pursued using data from a randomized controlled trial in Veterans with chronic pain (N = 116) randomly assigned to receive 8-week group ACT or CBT. Aim 1 identified a negative trend between the rate of change of pain and physical activity at baseline. Aim 2 did not find statistical support for a change in this relationship between pain and physical activity from baseline to post-intervention. Post-hoc analyses indicated substantial between-person variability and found that the pain-physical activity association changed from baseline to post-intervention for about half of participants, indicating this relationship is not static for all individuals. The Exploratory Aim qualitatively identified themes that supported the role of pain acceptance, activity pacing, and change in the pain-physical activity relationship. These findings suggest that the relationship between pain and physical activity is highly individualized and dynamic. Future studies should expand on these findings in larger samples and should apply idiographic approaches to better capture individualized patterns.

Introduction

Chronic pain is a highly prevalent and costly condition that adversely affects mental, physical, and social aspects of life. Chronic pain affected 20.9% of U.S. adults as of 2021 (Rikard et al., 2023), incurring national costs between $560 and $635 billion annually (Gatchel et al., 2014; Yong et al., 2022). Persistent pain is conceptualized as chronic when it lasts for more than three to six months (Merskey, 1986; Nicholas et al., 2019) and affects every day functioning (Cohen, et al., 2021; Patel et al., 2013; Turk et al., 2016). The diagnosis encompasses widespread pain (e.g., fibromyalgia), headache and orofacial pain, visceral pain (e.g., chronic pelvic pain), and musculoskeletal pain (e.g., chronic low back pain) and the factors thought to cause chronic pain are multifactorial, with biological, psychological, and social contributions (Nicholas et al., 2019). Pain has been divided into three main categories: Nociceptive, neuropathic, and nociplastic. Nociceptive pain is the most common, including conditions like arthritis, and is caused by damage to body tissue and ongoing inflammation (Cohen et al., 2021). Neuropathic pain stems from damage to the nervous system and includes conditions like diabetic neuropathy (Cohen et al., 2021; Finnerup et al., 2016). Nociplastic is the newest categorization and is defined as pain that does not result from observable tissue or nerve damage, but rather by altered pain modulation or processing and includes conditions like fibromyalgia and irritable bowel syndrome. While these categorizations have utility, they often overlap, resulting in a common "mixed pain" phenotype (Cohen et al., 2021; Fitzcharles et al., 2021).

Veterans specifically experience chronic pain at disproportionate rates (Rikard et al., 2023), with a prevalence rate of about 50% (Kerns et al., 2003; Taylor et al., 2024), and are more likely to experience higher intensities of pain (Nahin, 2017). Additionally, specific lifestyle factors (e.g., smoking, alcohol use), specifically in Veteran populations, have been associated with higher rates and/or intensity of chronic pain (Chapman & Wu, 2015; Kerns et al., 2003). Similarly, certain comorbid conditions that are prevalent in Veterans in conjunction with pain, such as traumatic brain injury and posttraumatic stress disorder (PTSD), have been associated with higher pain, disability, and suicidal ideation (Benedict et al., 2020; Blakey et al., 2018). Notably, chronic pain is associated with poorer physical function, an outcome emphasized for treatment in Veterans (U.S. Department of Veterans Affairs, 2009). Thus Veterans have been prioritized for study in the context of complementary and integrative health interventions for chronic pain by the National Center For Complementary and Alternative Medicine (National Center for Complementary and Integrative Health, 2021).

The impact of chronic pain is ubiquitous, and individuals living with chronic pain experience a host of negative impacts on mental health, suicide risk, social relationships, cognitive function, and life expectancy, all contributing to lower quality of life (Cohen et al., 2021; De La Rosa et al., 2024). Chronic pain conditions are associated with high rates of psychiatric comorbidity, particularly depression, anxiety, and PTSD (Aaron et al., 2025; De La Rosa et al., 2024; Mills et al., 2019) and almost all recognized psychiatric conditions have been found to exhibit increased chronic pain rates (Johnston & Huckins, 2022). The relationship between chronic pain and these conditions is thought to be bidirectional and share underlying mechanisms. For example, in depression, pain is associated with more depression symptoms and worse outcomes as well as more pain complaints and higher pain interreference. In line with this, neurobiological pathways, particularly the mesolimbic dopamine system, implicated in both depression and chronic pain have been suggested as overlapping mechanisms contributing to their interplay (Finan & Smith, 2013). Several psychological models attempt to explain the high co-occurrence of PTSD and chronic pain, across which catastrophizing emerges as a common factor (Johnston & Huckins, 2022). Pain catastrophizing is defined as a maladaptive coping response to anticipated or actual pain that consists of exaggerated negative cognitive and affective responses to the pain (Quartana et al., 2009). This represents a similar process to that of PTSD in which schemas representing fear guide interpretation of stimuli, altering one's attentional bias and resulting in a fear-driven interpretation of a neutral stimulus (Johnston & Huckins, 2022).

Treatments for Chronic Pain

Biomedical Treatments

Considering the pervasiveness and impact of this complex condition, a wide variety of treatments exist and personalized, interdisciplinary treatment is often recommended (Cohen et al., 2021). Prominent among these treatments are biomedical interventions such as non-surgical or minimally invasive intervention treatments (e.g., steroid injections, spinal cord stimulation), surgical procedures, and pharmacotherapy. However, these current biomedical treatments come with substantial limitations. The efficacy of non-surgical and surgical procedures depends on the type and pathology of pain being treated (e.g., neuropathic versus nociceptive; Cohen et al., 2021; Fitzcharles et al., 2021) and many patients continue to have persistent pain symptoms after these treatments or require repeat procedures (Cohen et al., 2021).

Pharmacotherapy, which includes opioids, poses the risk of misuse and abuse and only addresses short-term pain intensity rather than long-term functional improvement (Chou et al., 2020; Chou et al., 2015). One systematic review of the efficacy and harms of opioids in adults with chronic pain found opioid use to be associated with higher risk of overdose, abuse and dependence, fractures, myocardial infarction, and markers indicating sexual dysfunction, with some of these outcomes having higher risk with greater opioid use. This review also noted that most included studies were less than six weeks in duration and the review identified no studies that evaluated long-term outcomes related to pain or function (Chou et al., 2020). Veterans are at a particularly high risk for opioid misuse and abuse for a constellation of reasons including exhibiting higher rates of chronic pain and psychiatric comorbidities (Tam et al., 2020). As a result, nonpharmacological approaches to chronic pain management are at the forefront of chronic pain treatment (Mattocks et al., 2020). Given current limitations in the treatment of the pain itself, it has been important to consider shifting the emphasis of treatment from attempts to eliminate pain to a goal of improving function despite the presence of pain.

Psychological Treatments

Cognitive-behavioral interventions such as Cognitive Behavioral Therapy (CBT) and Acceptance and Commitment Therapy (ACT) are increasingly relied on to optimize chronic pain management. These interventions do not reduce pain per se, but seek to maximize physical, social, and occupational functioning by addressing pain-related thoughts, beliefs, and behaviors (Hayes et al., 2006; Hughes et al., 2017). CBT is the current gold standard cognitive behavioral intervention for chronic pain (McCracken & Morley, 2014). The CBT model consists of three interconnected components (**Figure 1**): self-defeating thoughts and beliefs, negative emotions, and maladaptive behaviors. Each of these components influence one another in a bidirectional cycle in which CBT treatment can intervene with the rationale that one's subjective experience of pain can be decreased by controlling some of these contributing factors (Stewart et al., 2015). Traditional CBT interventions for chronic pain will generally include 1) a cognitive component in which self-defeating beliefs about, and repetitive thoughts related to, pain are identified and reappraised; 2) an emotional regulation component in which the patient is taught coping skills to utilize when exposed to the negative thoughts about pain; 3) a behavioral activation component used to increase engagement with rewarding activities outside of pain; and 4) a problem solving

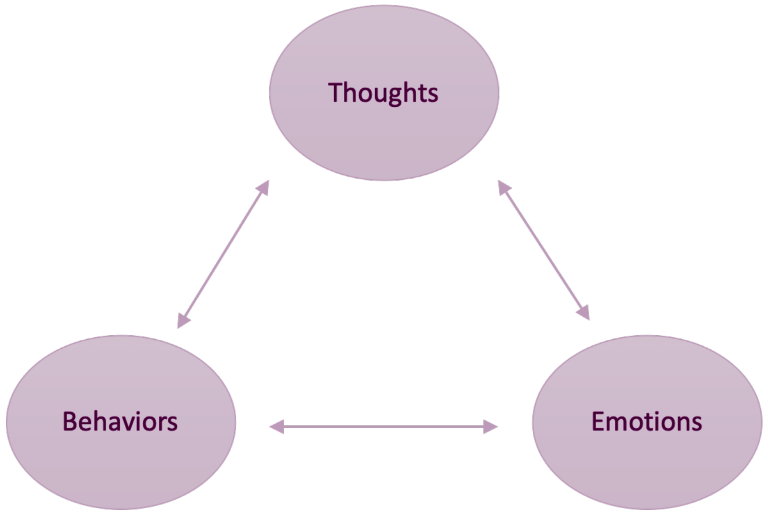

Figure 1: Cognitive-behavioral conceptualization of chronic pain.

and motivation component (Otis, 2007; Williams et al., 2020). In line with these component, CBT for chronic pain includes teaching a variety of techniques such as pain monitoring, activity pacing, increasing pleasant activities, relaxation (e.g., guided imagery, breathing, progressive muscle relaxation), thought challenging, and problem skills training (Herbert et al., 2022). Thus, CBT for chronic pain targets pain's interference on function through techniques related to each of the three model components. These techniques should be practiced in order to apply them to everyday contexts, troubleshoot, and encourage independence or continuation of the techniques after the termination of therapy. Therefore, practicing these techniques, in the form of homework assignments, is standard (Bergin & Garfield, 1994; Kazantzis et al., 2010).

ACT is a mindfulness-based cognitive behavioral approach that has shown efficacy for a variety of mental and physical health conditions (e.g., depression, anxiety, smoking cessation; Hayes et al., 2012) and has been found to be equally as effective as the gold-standard psychosocial therapy for chronic pain (traditional CBT) with respect to relevant outcomes: pain interference, depression, and pain-related anxiety (Wetherell et al., 2011). ACT is a "third-wave" approach that differs from “second-wave” CBT in that it does not attempt to reappraise or change thoughts (the cognitive component of CBT) but rather focuses on one’s relationship to these thoughts. More specifically, it aims to increase “psychological flexibility”, which is one’s ability to change or persist in behavior in the presence of unpleasant internal experiences (e.g., pain; Hayes et al., 2006) and thus ACT is fundamentally tied to function. ACT seeks to target six distinct but interrelated treatment processes that subsequently increase psychological flexibility (**Figure 2**) and thereby positively influence function. Three of these make up the “mindfulness and acceptance processes” that work to promote a non-judgmental embrace of internal events without trying to change them [acceptance], change how one relates to these thoughts [cognitive defusion], and separate the conscious self from one’s thoughts [self-as-context]. The other three make up the “commitment and behavior change processes” that emphasize non-judgmental experience of external events [present moment contact] and performance of goal-directed behaviors [committed action] that are in line with personally held values [values] (Hayes et al., 2006; Hayes et al., 2011). ACT’s effect on chronic pain has been found to be mediated by psychological flexibility and, like in CBT, practice of the relevant concepts is expected (Hayes et al., 2022; Lin et al., 2018; Vowles et al., 2014).

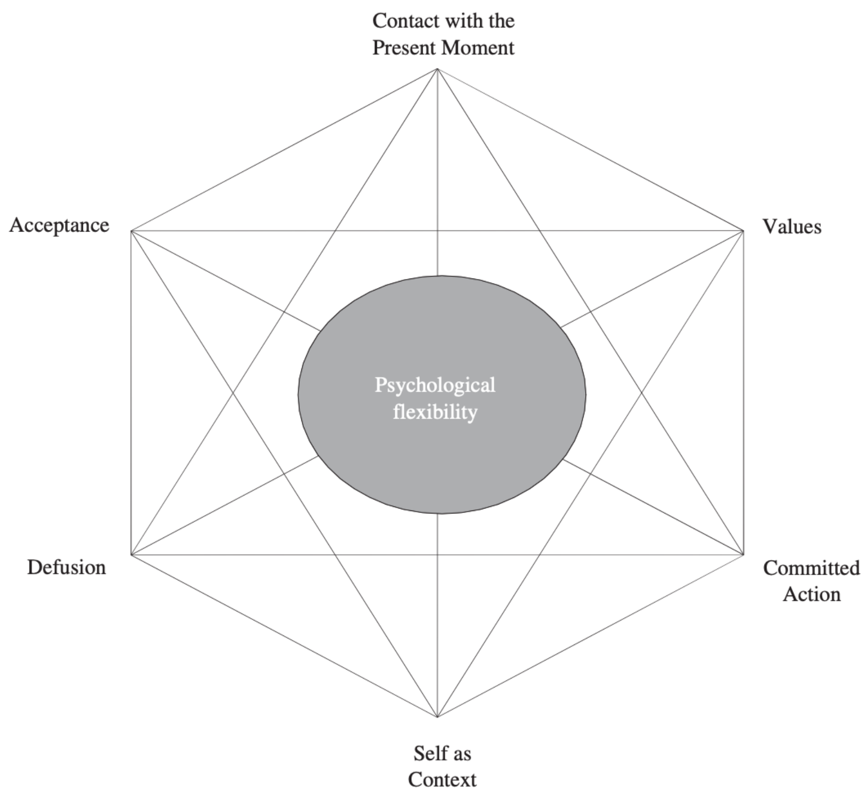

Figure 2: ACT model of psychological flexibility. Adapted from Hayes et al, 2006.

Both and CBT and ACT can both be delivered in either an individual or group format (Hughes et al., 2017; Knoerl et al., 2016). Conducting these treatments in a group format may provide benefits such as support and validation from other group members, increased accountability, and cost-effectiveness. Both treatments can also be delivered either in-person or virtually (i.e., telehealth; Mariano et al., 2019; Rosser et al., 2023), a consideration that has become increasingly relevant since the Covid-19 pandemic. Telehealth offers several benefits, including increasing access (McGeary et al., 2012), such as servicing individuals who are remote, or who struggle to get services due to geography or time constraints. Virtually delivered CBT has been found to be non-inferior to in-person delivered treatments in conditions like insomnia (Arnedt et al., 2020) and similar outcomes have been observed in in-person versus virtual CBT for fibromyalgia (Vallejo et al., 2015). Virtually delivered ACT for chronic pain has been shown to be non-inferior to in-person delivered treatments with regard to pain interference, health-related quality of life, and chronic pain acceptance (Herbert et al., 2017). Therefore, the use of both group and virtual delivery in chronic pain populations is feasible and increasingly common.

Although there is substantial evidence for both ACT and CBT as safe and effective for the management of chronic pain, these interventions are not effective for every individual and the understanding of how they work is limited. Various reviews have been conducted examining the efficacy of CBT and ACT in chronic pain populations, however they vary in types of interventions and included outcomes, with many examining pain intensity, disability, quality of life, anxiety, and depression, but fewer measuring specific aspects of function (Martinez-Calderon et al., 2024; Wang et al., 2025). Regarding CBT, a systematic review found evidence for the efficacy of traditional CBT in depression, anxiety, and quality of life, but, importantly, this review did not find a significant impact on pain intensity and pain catastrophizing, and found insufficient evidence on function, which was only measured as social functioning (Sanabria-Mazo et al., 2023). Similarly, a systematic review of ACT for chronic pain found only small to medium effect sizes for functioning, anxiety, and depression, with smaller effect sizes at follow-up, and did not find a significant effect on pain intensity and quality of life (Hughes et al., 2017). The studies included in this review measured "functioning" using a variety of questionnaires assessing pain disability, interference, and/or impairment. Another meta-analytic review examined acceptance and mindfulness-based interventions more broadly, 12 of which were ACT, and found small to moderate effect sizes in favor of intervention on pain intensity, depression, anxiety, pain interference, disability, and quality of life, but this review did not examine function (Veehof et al., 2016). A review of online-based ACT for chronic pain similar found small to medium effects of depression, pain interference, pain acceptance, mindfulness, and psychological flexibility, but found insufficient data to report on functioning (Trindade et al., 2021). Taken together, these reviews highlight the insufficiency of these interventions as well as the lack of prioritized investigation of function as an outcome. Thus, it is necessary to better understand how such interventions are working to bolster these effect sizes, improve existing and future cognitive behavioral treatments, and examine if and how they impact function.

Pain Acceptance as a Putative Mediator of Improved Function

Pain-related acceptance has been identified as an important variable in the context of chronic pain (Åkerblom et al., 2015; Baranoff et al., 2013; McCracken, 2024; Vowles et al., 2014), but little is known about how acceptance may impact function specifically and how this treatment process is perceived and experienced by those undergoing these treatments. Pain acceptance is defined as the willingness to experience pain without fighting against it (Hayes et al., 2006; Hughes et al., 2017). This acceptance then frees the individual to disengage from pain and instead engage with valued life activities, thereby increasing psychosocial functioning broadly. In the context of no intervention, pain acceptance has been found to mediate the relationship between momentary pain and pain interference such that individuals with high pain acceptance experience less pain interreference in their day-to-day lives (Kratz et al., 2017). This same study found similar results in the relationship between momentary pain and an indicator of physical functioning, indicating that pain acceptance decouples the relationship between momentary pain and various conceptualizations of functioning (e.g., general, physical). Acceptance is a treatment process directly and intentionally targeted in ACT (Hayes et al., 2006), but not in CBT. However, pain-related acceptance has been found to be a key mediator in both types of intervention (Baranoff et al., 2013; Vowles et al., 2014; Wetherell et al., 2011), over and above the impact of several intended targets of CBT including life control, affective distress, and social support (Åkerblom et al., 2015) and is thought to be influenceable by both interventions (McCracken, 2024). This indicates that pain acceptance is an important therapeutic process for the management of chronic pain that is alterable both directly by ACT and indirectly by CBT. See **Table 1** for some of the methods by which ACT and CBT may impact pain acceptance.

Table 1: Potential Therapeutic Methods Through Which ACT and CBT May Impact Pain Acceptance

ACT	CBT
Acceptance	Behavioral activation
Present moment awareness	Challenging interfering behaviors and beliefs
Defusion	Pain psychoeducation
Self-as-context	Promote self-efficacy

Frustratingly, ACT and CBT still fall short on achieving more than just moderate effect sizes for changes in some metrics of functional improvement (e.g., pain disability; Hughes et al., 2017), self-report measures of pain acceptance and function suffer from low psychometric quality (Reneman et al., 2010), and little is known about subjective patient experiences of pain acceptance within ACT and CBT. Thus, more research is needed to articulate the mechanisms underlying successful intervention for chronic pain so that these factors can be bolstered and emphasized to improve current treatments.

Function in Chronic Pain

The impact of chronic pain on function is wide in scope, encompassing physical, emotional, and social functioning. Indicators of physical function are particularly important because they reflect the impact of pain and treatment beyond self-reported symptom reduction and can indicate one's overall functional status and quality of life, including the ability to perform activities of daily living, work, engage in self-care, and spend time with important others (Taylor et al., 2016). Despite the importance of function as an outcome in chronic pain treatment, current research is limited by the use of self-report measures of function that lack ecologically validity and a prioritization of emotional functioning over physical or social functioning as reflected in selected outcome measures (Hann & McCracken, 2014; Lai et al., 2023; Ma et al., 2023). Physical function is not precisely defined in the literature and is often assessed using self-report ratings of the amount of interference from pain in daily life (Taylor et al., 2016).

Physical Activity

One important component and indicator of function is physical activity, as reflected in pain interference measures (e.g., how much pain interferes with general activity, walking ability, and work). Thus, there is rationale to expect a relationship between pain and physical activity, but prior research has revealed discrepancies in this association. In non-chronic pain samples, one review failed to find evidence for an association (Sitthipornvorakul et al., 2011), another review found higher physical activity to be associated with higher risk of pain (Øverås et al., 2020), and yet another found leisure physical activity to be associated with lower risk of pain (Shiri & Falah-Hassani, 2017). In a low back pain population, medium physical activity level (between 33^{rd} and 66^{th} percentile for the sample) was associated with less risk of pain than lower physical activity, but this was not observed for high physical activity and was present only in longitudinal (not cross-sectional) studies (Alzahrani et al., 2019). There is also evidence for a bidirectional relationship between pain and physical activity. One study identified a dose-response relationship between number of pain sites and less moderate and vigorous physical activity and more low intensity physical activity (Pan et al., 2019). A second study found more pain sites to be associated with lower step count and less objectively measured moderate-vigorous physical activity in older adults (Murata et al., 2019). However, other studies observed no such association between pain duration, intensity, or number of sites and objectively measured physical activity (Aebischer et al., 2022).

Ambulatory Assessment

Research design choices may contribute to mixed findings (Perruchoud et al., 2014). Many studies rely on retrospective self-report of pain and physical activity, which lack ecological validity, generalizability to daily life, and limit the understanding of temporal dynamics (Shiffman et al., 2008; Stone et al., 2021). Moreover, retrospective self-report measures lack objectivity and are subject to recall and social desirability bias (Reichert et al., 2020; Shiffman et al., 2008), all of which may obscure the pain-physical activity relationship (Shiffman et al., 2008; Stone et al., 2021). To address such issues, researchers have moved toward ambulatory assessment, which offers promise for better understanding associations between behaviors (e.g., physical activity) and experiences (e.g., pain) in naturalistic contexts. Ambulatory assessment includes ecological momentary assessment (EMA), actigraphy, wearable devices, and other longitudinal data collection methods (e.g., heart rate variability) that depict real-time, real-world relationships between measured variables (Trull & Ebner-Priemer, 2013). Ambulatory assessment facilitates the examination of within-person associations between variables (Reichert et al., 2020) such as "are people in more pain when they do more physical activity than their average?" distinct from the between-person level (e.g., "do people who do more physical activity have more pain?"). Ambulatory assessment of physical activity collected via actigraphy has been used as an objective indicator of function (Agarwal et al., 2007; Dunlop et al., 2014; Wilson & Palermo, 2012). In one innovative study, objective physical activity was integrated with pain ratings collected via EMA to understand the real-time, real-world relationship between pain and physical activity. Momentary physical activity was negatively associated with momentary pain, and this relationship was attenuated by pain acceptance, a treatment target of ACT (Kratz et al., 2017). This suggests the pain-physical activity relationship is dynamic and needs to be more thoroughly examined. Moreover, this study only examined these associations at one timepoint, therefore even less is known about if and how this relationship can be altered over time by cognitive behavioral intervention.

Summary and Gaps in the Literature

In summary, chronic pain is a pervasive and significant problem in the United States that represents a research priority. The goal of psychosocial treatments for chronic pain, such as CBT and ACT, is to improve one's functioning, or how one lives with pain. Physical activity is one indicator of function in this context and ecologically valid methods of measuring physical activity and pain (i.e., ambulatory assessment) offer promise for examining the relationship between these two constructs in a more nuanced and temporally dynamic way. However, current research lacks a thorough understanding of functional improvement in chronic pain. Moreover, the dynamic relationship between pain and physical activity in individuals' experience of chronic pain is not well characterized or examined over the course of intervention, potentially limiting the understanding and efficacy of chronic pain treatment (Hayes et al., 2022; McCracken, 2024). Although ambulatory assessment offers promise for better characterizing the pain-physical activity relationship, this remains a relatively nascent area. Reviews have examined specific ambulatory assessment methods (e.g., EMA or actigraphy) in chronic pain and have highlighted the promise of these methods but also identified shortcomings, such as heterogeneity between studies and a lack of nuance in the statistical methods used to analyze these intensive data (May et al., 2018; Tynan et al., 2023). Finally, there is a dearth of qualitative research to better understand the lived experience of this relationship between pain and physical activity, especially in the context of nonpharmacological chronic pain treatment. Prior qualitative studies conducted after cognitive behavioral treatment for pain have focused on the participants' perception of the intervention, its acceptability, and ways to improve it (Day et al., 2011; Egan et al., 2016; Fraser et al., 2019; Tsubaki et al., 2023). However, in general, these studies did not focus on patients' perceptions of the therapeutic mechanisms targeted by treatment or of their functioning. Some themes emerged related to functioning, such as a perceived impact of intervention on how participants thought about or related to pain (Fraser et al., 2019), and a sense of autonomy that led to an increase in physical activity (Tsubaki et al., 2023). Further qualitative work is needed to delve more into the perceived relationship between pain and function, or physical activity, in the context of chronic pain treatment.

In response to this, the research completed for this dissertation seeks to 1) characterize the real-time relationship between pain and physical activity, 2) examine the extent to which participation in cognitive behavioral intervention changes the real-time dynamic relationships between pain and physical activity, and 3) conduct qualitative interviews to explore perceived factors driving the effect of intervention on function (e.g., pain acceptance), thereby contributing meaningfully to the evidence base of cognitive behavioral treatments for chronic pain. Together, this research aims to fill key gaps by enhancing the understanding of functional improvement in cognitive behavioral interventions and therefore advance the treatment of chronic pain. Better assessing and understanding the relationship between pain and physical activity both statistically and qualitatively will allow for a more nuanced and individualized approach to the treatment of chronic pain, spur new areas of scientific exploration, and ultimately transform cognitive behavioral treatment of chronic pain and other chronic conditions.

Current Research

Parent Study

The research completed for this dissertation was conducted in the context of a trial of a meditation-enhanced group ACT intervention for Veterans with chronic pain, namely ACTing with Mindfulness for Pain (AMP; Herbert et al., 2022). Participants (N = 116) were randomized to receive either AMP, an eight-week group-based ACT intervention in which participants were instructed in how to engage in formal mindfulness meditation practice and were expected to practice daily and keep a meditation diary, or traditional CBT for chronic pain (CBT-CP). Participants are Veterans with heterogenous chronic pain. Veterans experience chronic pain conditions at a disproportionate rate (Kerns et al., 2003; Rikard et al., 2023), making them an apt and important population in which to conduct chronic pain research. Because cognitive behavioral interventions seek to address individuals' relationship to pain, rather than the pain itself, and because of the frequent comorbidity of pain conditions, it is appropriate to examine heterogenous chronic pain as opposed to a single discrete pain condition. This trial was conducted to establish feasibility of a future large-scale trial and estimate the preliminary impact of AMP with regard to the primary outcome, pain interference, as measured via self-report. Actigraphy and EMA measures were collected over two separate seven-day intervals at both baseline and post-intervention (see **Figure 3** and Aim 1 Measures below).

ACT Intervention (AMP). AMP is an eight-week virtually delivered, group-based intervention that was adapted from traditional ACT and developed based on clinical experience. Participants were introduced to mindfulness and instructed in how to engage in formal practice (i.e., sitting medication and body scan meditation). After the first session, participants were expected to practice formal mindfulness meditation daily, initially using provided audio recordings and later without recordings, and to complete a daily meditation diary. Topics for weeks two through eight address the various psychological flexibility processes using experiential methods from ACT, using the formal mindfulness meditation practice to support values-based living. Thus, the relationship between formal mindfulness practice and the psychological flexibility processes was consistently reinforced. Each session was 90 minutes and consisted of a formal mindfulness meditation practice (10-15 minutes), a review of homework and previous topics (10-15 minutes), experiential exercises and discussions of a treatment topic (35-45 minutes), and closed with an informal mindfulness exercise and formal mindfulness meditation sitting (10-15 minutes).

CBT Intervention (CBT-CP). The CBT-CP comparison group used an eight-week, virtually delivered, 90-minute session, manualized protocol developed at the VA San Diego Healthcare System and used in previous research (Wetherell et al., 2011). This protocol is based on the three-component CBT model (thoughts, feelings, behaviors) with the rationale that controlling some of the factors that contribute to pain can lead to a decreased subjective experience of pain (Stewart et al., 2015). CBT-CP focused on training participants to manage their pain using a variety of techniques, including pain monitoring, pacing, increasing pleasant activities, progressive muscle relaxation, thought challenging, and problem skills training. The net result of these strategies was to control pain by changing its physical, cognitive, behavioral, and emotional precursors, leading to reduced pain severity, and resulting in beneficial consequences on pain interference, quality of life, and physical activity. Similar to AMP, CBT-CP emphasized the importance of at-home practice assignments to develop skills taught in session.

Aims of the Current Proposal

The current dissertation is a secondary analysis and novel extension of the parent study to examine actigraphy and EMA data collected at baseline and post-intervention to characterize the relationship between pain and physical activity and by adding a recontact period to conduct qualitative interviews.

Aim 1 sought to characterize the dynamic, time-dependent relationships between pain and physical activity as measured using ambulatory assessment in a sample of Veterans with chronic pain. Structural equation modelling (SEM) was used to model the relationship between EMA pain and objective physical activity within-person at baseline. These findings can inform the understand of the relationship between pain and physical activity in chronic pain populations.

Aim 2 sought to examine the relationships between pain and physical activity in the same sample after intervention to ascertain if these relationships are alterable by intervention. This was accomplished with the application of SEM that allows for the examination of longitudinal patterns of change in pain and physical activity and how they relate to one another before and after intervention. These findings can inform the improvement, development, and application of cognitive behavioral treatments for chronic pain. Together, Aims 1 and 2 address a specific gap in the literature regarding the relationship between pain and physical activity in Veterans with chronic pain and whether this relationship can be altered with targeted cognitive behavioral intervention.

Aim 3 qualitatively assessed how individuals relate to their pain and if intervention had any impact on this experience during the elapsed time since the intervention. Qualitative research holds promise for complementing the quantitative findings of the current proposal by examining if changes in a quantitative indicator of function in the presence of chronic pain are accompanied by subjectively experienced changes. In addition, this qualitative work can inform the field of the subjective experience of chronic pain after cognitive behavioral intervention.

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Method

Aim 1: Use actigraphy and EMA to characterize real-time relationships between pain and physical activity in Veterans with chronic pain prior to treatment.

Hypothesis: Over the 7-day baseline period, the growth trajectories of pain and physical activity will be related such that increases in pain will be associated with decreases in physical activity.

Inclusion and Exclusion Criteria

Inclusion and exclusion criteria are identical to that of the parent study, AMP. Inclusion criteria for the parent study are (1) Diagnosis of a chronic, nonterminal pain condition; (2) Pain most days (> 3 days/week) for at least 6 months; (3) Average pain severity and interference with enjoyment of life and/or general activity > 4/10 over the past week, as measured by the PEG (Krebs et al., 2009). Exclusion criteria include 1) serious or unstable medical or psychiatric illness, 2) active suicidal ideation or history of suicide attempt in the last 3 years, 3) psychosocial instability that could compromise study participation (e.g., homelessness), 4) current participation in group psychotherapy for pain or any type of individual psychotherapy, and 5) changes to professionally delivered pain or mood treatments within the past month. Participants must have sufficient valid actigraphy and EMA data (>20% valid) for use in analysis.

Procedures

Data to address Aims 1 and 2 were collected from the parent RCT comparing the 8-week AMP and CBT interventions. The completed data collection was supported by Dr. Herbert's VA funding (#1IK2RX002807; *N* = 116). See **Figure 3** for study flow. Following informed consent, participants were mailed an actigraph and instructed to wear it continuously for at least seven days prior to starting the first session of their assigned intervention (AMP or CBT). Following completion of the eight-week protocol, participants were again mailed an actigraph and instructed to wear it for another seven days before mailing it back. Momentary pain ratings were also collected during these two seven-day periods using the actigraph device.

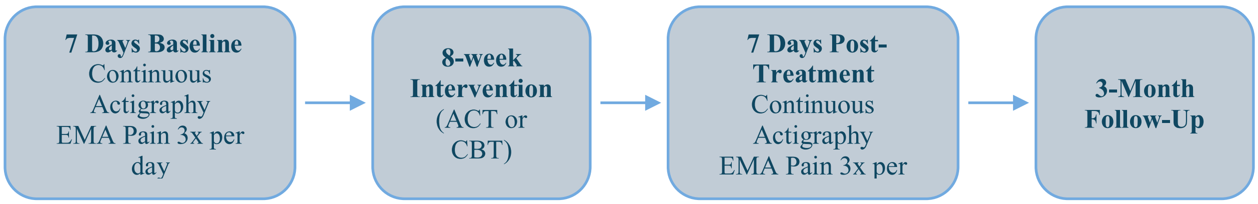

Figure 3: AMP study flow.

Measures

Actigraphy. Actigraphy data were collected by the Actiwatch Spectrum PRO 3 wrist accelerometer. The actigraph collects movement counts (i.e., accelerometry) and light exposure continuously in 30-second epochs and has a skin capacitance sensor to detect removal. The key actigraphy outcome is the activity count (ac) from each active interval, averaged across relevant activity windows tied to corresponding EMA pain ratings (i.e., momentary physical activity), excluding periods of missing data that occur due to temporary removal of the device. For purposes of interpretation, cut-offs were used for sedentary (<80 ac) light (80 ac to <262 ac), moderate, (262 ac to <406 ac) and vigorous physical activity (>406 ac; Ekblom et al., 2012; Kemp et al., 2020).

EMA. EMA ratings of pain intensity were collected on the Actiwatch Spectrum PRO 3 times per day at predetermined times (10am, 2pm, 7pm) during the seven days at baseline and post-intervention. At these times, participants' actigraphs alerted them to rate their current pain intensity by selecting a number on a scale from 1-10 on the device. Study staff trained participants on how to use the devices and respond to the scale appropriately.

Pain Acceptance. Pain acceptance in the context of chronic pain was measured using the Chronic Pain Acceptance Questionnaire-revised (CPAQ), a 20-item self-report measure

(McCracken et al., 2004). The CPAQ yields both a total score and two subscale scores: Pain Willingness, define, and Activity Engagement, the extent to which an individual pursues life activities regardless of pain. Items are rated on a 7-point Likert scale ranging from 0 “never true” to 6 “always true” and higher scores indicate greater pain acceptance. The CPAQ demonstrated good internal consistency in the current sample (Herbert et al., In preparation).

Data Analyses

Data Preparation. Each participant’s data file was manually screened to determine valid wear time. Within each day, EMA pain ratings and actigraphy data within a four-hour window of the ratings (2 hours before each pain rating and 2 hours after) was marked for use in analyses, similar to previous studies (Kratz et al., 2017). Average activity counts were calculated across each interval (three intervals per day), resulting in three pain ratings and three activity scores representing data from a total of 12 hours each day.

Preliminary models conducted with these variables identified collinearity issues due to the high number of timepoints and strong correlations between variables across these timepoints. Eigenvalue decomposition for the correlation matrices for the pain and physical activity variables reveled negative and near-zero eigenvalues, indicating multicollinearity and preventing the model from converging. Therefore, pain ratings and activity scores were averaged within days to yield seven average pain ratings and seven average activity scores (one per day) for each participant. This ameliorated the collinearity issues and allowed the models to converge.

The Shapiro-Wilk test was used to assess normality of pain and physical activity variables across all timepoints. Results indicated significant deviations from normality for eight of the 14 variables at baseline and five of the 14 variables at post-intervention, which is common in behavioral health datasets (Tabachnick & Fidell, 2019). As a result, robust maximum likelihood (MLR) estimation was used instead of maximum likelihood estimation that assumes multivariate normality. MLR is robust to such violations of normality and allows for the inclusion of all available data. Missing data were handled using full information maximum likelihood.

Latent Growth Curve Model Estimation. To characterize the dynamic, time-dependent relationships between momentary pain and momentary physical activity at baseline, latent growth curve models (LGCM) were used. First, separate LGCMs were estimated for pain and physical activity variables separately to examine the growth trajectories of each variable over the seven-day baseline period independently. Next, a parallel LGCM was used to examine the association between momentary pain and momentary physical activity over the same seven-day baseline period (see **Figure 4** for path details). Parallel LGCMs fit two latent growth curve models and allow for the correlations between the growth factors (i.e., growth intercepts [baseline or average value] and slopes [change per unit of time]; McArdle, 2009). In this way, the parallel LGCM can account for several multivariate relationships: 1) the correlation between the intercepts of the two variables (**Figure 4**, path A), or the relationship between pain and physical activity at the first timepoint; 2) the relationship between the intercept and the slope of each variable (**Figure 4**, path B), or the relationship between pain at the first timepoint, and its change over time, and the relationship between physical activity at the first timepoint and its change over time; 3) The relationship between the intercept of one variable and the slope of the other (**Figure 4**, path C), for example, the relationship between pain at the first timepoint and change over time of physical activity and vice versa; and 4) relevant to the current study, the relationship between the slopes of both variables (**Figure 4**, path D), or the relationship between the rate of change of pain and the rate of change of physical activity over the seven days. A negative correlation path between the pain and physical activity slopes in Figure 4 (path D) would support the hypothesis for this aim.

Power Analysis and Sample Size Considerations. Calculations of sample size estimates for SEM and LGCM are complex. Compared to traditional factor analysis models, sample size requirements are reduced as the factor loadings of the observed variables onto the latent variables are fixed, decreasing the number of parameters to be estimated in the model to the mean and variance of the intercept and of the slope, the covariance between the intercept and slope, and three error variances (Duncan & Duncan, 2009). Researchers have successfully fitted LGCM in similarly sized samples (Batchelder et al., 2022; Chien et al., 2021; Mathur et al., 2021) and in samples as small as n = 22 (Curran et al., 2010).

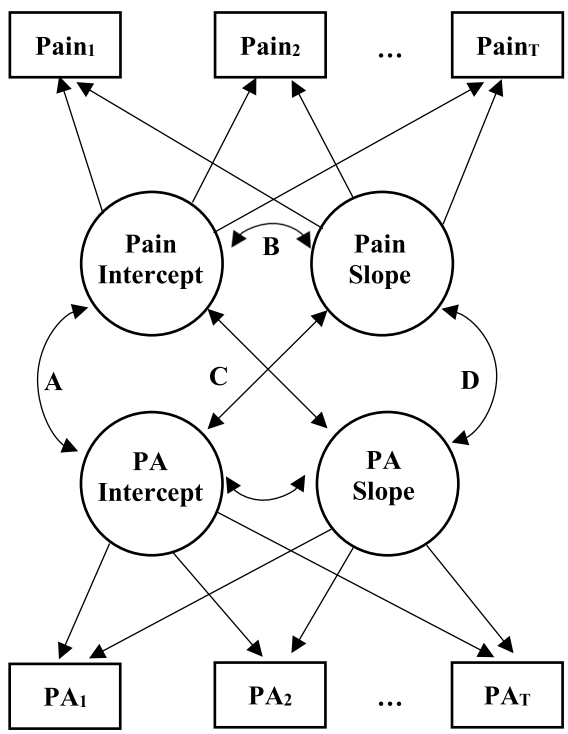

Figure 4: Path details of the parallel LGCM of the relationship between pain and physical activity (PA).

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Aim 2: Examine the extent to which participation in cognitive behavioral intervention changes the real-time dynamic relationships between pain and physical activity.

Hypothesis: Over the 7-day post-intervention period, the relationship between growth trajectories of pain and physical activity will be altered compared to baseline.

Data Analyses

To characterize the dynamic, time-dependent relationships between momentary pain and momentary physical activity at baseline, LGCM were used. First, separate LGCMs were estimated for pain and physical activity variables separately to examine the growth trajectories of each variable over the seven-day baseline period independently.

Latent Growth Curve Model Estimation. As in Aim 1, separate LGCMs were first estimated for pain and physical activity variables separately using data from the seven-day post-intervention period. Next, the same parallel LGCM used in Aim 1 was applied to the data from the seven-day period post-intervention. However, during the model estimation process, this model not able to converge in the post-intervention dataset as specified. Upon inspection of the parameter estimates, it was determined that a negative variance was being estimated with the slope of physical activity at the post-intervention timepoint. Since negative variance estimates are not interpretable within the context of LGCM, the model was not able to converge. To address this, the variance of the slope of physical activity at post-intervention was constrained to be equal to its variance at baseline. This assumes consistent variability in the rate of change of physical activity both at baseline and post-intervention and resolved the convergence issue, allowing the model to produce interpretable parameter estimates. See Appendix A for the covariance and variance estimates from the non-converged parallel LGCM at post-intervention.

Multiple Group SEM. To examine if intervention affects the relationship between the pain and physical activity slopes, a multiple group SEM analysis was conducted. Specifically, to test the null hypothesis that the parameter of interest (Figure 4, path D) can be constrained to be equal across time, A Wald test (1 df chi-square) was used to test equivalence. First, an unconstrained model was fit, grouping the data by time point. However, this model produced negative variance estimates, potentially indicating an empirical under identification issue. Next, a model imposing equality constraints across all structural and measurement parameters (e.g., factor loadings, intercepts, means, residuals, covariances) was fit. A Wald test was conducted using this fully constrained model to evaluate whether the observed difference in the parameter of interest is statistically different from baseline to post-intervention. Other, partially constrained, models were also tried, but none produced convergence.

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Exploratory Aim: Qualitatively explore perceived factors driving the effect of intervention on function using thematic analysis.

Inclusion Criteria

Completed participation in the study through the 3-month follow-up assessment with sufficient valid actigraphy, defined as those who attended at least six sessions and who have five days or more of valid actigraphy data at both pre- and post-intervention timepoints.

Procedures

12 months after their completion of post-intervention activities, intervention completers were contacted by telephone to provide information about follow-up interviews. Interviews inquired about perceived changes in function and pain management and focused on eliciting information on the participants' relationship with pain, their everyday functioning and physical activity, and any changes noticed over the course of, or since, the intervention. Interview guides were developed by the PI with consultation from a qualitative consultant with vast experience in qualitative methods (JP). The interview guide was piloted on a research assistant who was a Veteran (AH) and feedback was incorporated to alter the order of certain questions. Participants were contacted from both AMP and CBT groups. Efforts were made to select a group representative of the sample in terms of sex, race, and age. Eligible and consenting participants were scheduled to have a one-on-one interview conducted over the phone, in line with procedures used to acquire post-intervention and 3-month follow-up measures. Interviews were conducted until saturation was achieved (N = 15). Interviews lasted 15-30 minutes and were all conducted by the PI, a female advanced clinical psychology doctoral student trained in qualitative methods and experienced in chronic pain research. The PI had not had prior contact with the research participants. See **Table 2** for examples of questions used to guide interviews

and see Appendix B and Appendix C for full interview guides for participants from ACT and CBT groups.

Table 2: Example Qualitative Interview Questions to be Administered via Telephone 12 Months Post-Intervention

When engaging in day-to-day activities now, how are you able to manage your pain?
What gets in the way of you managing your pain now?
What influence did the intervention have on your amount of activity including going on walks, getting out of the house, exercising, completing household chores, and spending time with friends or family?
How has your relationship with pain changed since being in the group?

Recorded telephone interviews were transcribed by two undergraduate psychology research assistants (RV and SF) with consultation from the PI to observe initial patterns in the data and prepare the data for thematic analysis.

Data Analysis

Qualitative data were analyzed using Atlas.ti, a qualitative data analysis software package. This program was used to conduct thematic analysis, which involves identifying patterns within qualitative data, systematically coding the data, and then identifying themes and sub-themes within the data. Codes were developed from patterns observed in the transcripts, with attention given to responses that reflect perceived key factors in the relationship between pain and physical activity as inquired by the interviews. Initial codes were developed by two coders who met every two weeks, the PI and a research coordinator with a bachelor's degree in clinical psychology (EM) with consultation from JP. For each transcript, the PI and EM independently marked and labeled quotations by the code that best corresponded to the quotation's meaning. After independent labelling, discrepancies were discussed between the PI, EM, and JP and consensus was reached. The codes were adjusted and revised during this process through conversation between all qualitative team members at regular meetings. The labeled quotations were then sorted and grouped, so that concepts, then themes and sub-themes were developed from the participant responses. Themes were developed inductively, with ongoing comparison across transcripts. This process of sorting and grouping labelled quotations was initially conducted independently by the PI and EM and consensus was reached through discussion with consultation from JP. Where there was conceptual overlap between sub-themes under different themes, the sub-theme was assigned to the theme that better fit the theoretical framework and conceptual meaning of the sub-theme, which was determined through conversation amongst the qualitative team, using cognitive behavioral theory to guide relevant decisions. As is often standard practice for qualitative data analysis, analysis was concurrent with data acquisition, as described. Such iterative analyses ensure sufficient extraction of the qualitative information provided by participant interviews. Items from the Consolidated Criteria for Reporting Qualitative Research (COREQ; Tong et al., 2007)) were used to increase transparency, rigor, and reproducibility of the current qualitative analyses. See Appendix D for the full COREQ checklist.

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Results

Sample Descriptive Statistics

A total of 116 U.S. Veterans were enrolled (AMP *n* = 75, CBT *n* = 41) and completed baseline assessments in the parent study. Of these, 29 were enrolled as part of Phase 1 during which the AMP protocol was piloted and refined and 87 were enrolled in the pilot RCT comparing AMP with CBT for chronic pain (AMP *n* = 46, CBT *n* = 41) The overall sample was mostly male (77.0%) with an average age of 49.44 (SD = 12.42) years. The largest proportion of the sample identified as non-Hispanic White (41.4%), nearly 30% identified as Black or African American, and 16.1% identified as Hispanic or Latinx. Of the 116 enrolled, 92 provided some amount of actigraphy and EMA data (i.e., more than one pain rating completed) at baseline or post-intervention. At baseline, 85 provided sufficient actigraphy data (i.e., at least 80% valid actigraphy) and at least one pain rating to be included in present analyses. This subsample had an average of 88.8% valid actigraphy and completed on average 85.8% of EMA pain ratings. At baseline, participants had an average pain rating of 5.60 out of 10 (SD = 2.14, range: 0-10) and an average actigraphy count of 218.37 ac (SD = 136.32, range: 0-934) which corresponds to "light" physical activity (Ekblom et al., 2012; Kemp et al., 2020).

At the post-intervention timepoint, 59 participants provided sufficient valid actigraphy and EMA data to be included in analyses, six of whom did not have sufficient valid data at baseline. Post-intervention, this subsample of participants had an average of 80.8% valid actigraphy and completed on average 79.7% of EMA pain ratings. At post-intervention, participants had an average pain rating of 5.28 out of 10 (SD = 2.29, range: 0-10) and an average activity count of 224.51 (SD = 129.90, range: 0-896.39). Change in average pain from baseline to post-intervention was -0.32 (SD = 1.84, range: -5.29-5.95) and change in average physical activity from baseline to post-intervention was 6.14 (SD = 75.21, range: -219.74-203.80). There were no significant differences across groups in participants having both baseline and post-intervention data ($\chi^2(1) = 0.08$, $p = 0.78$).

Aim 1: Use actigraphy and EMA to characterize real-time relationships between pain and physical activity in Veterans with chronic pain prior to treatment.

Baseline Individual Growth Trajectories

Pain. The individual LGCM for pain demonstrated good model fit (scaled $\chi^2(23) = 25.50$, $p = 0.33$ [Yuan-Bentler correction], SRMR = 0.035, robust RMSEA = 0.000 [90% CI [0.000, 0.130]], robust CFI = 1.00, robust TLI = 1.00). The mean growth intercept for pain was significantly different from zero (5.60, SE = 0.21, $p < 0.001$) while the slope was not significantly different from zero (-0.02, SE = 0.02, $p = 0.49$). The intercept suggests that, on average, participants initially reported a moderate level of pain at baseline however the lack of significant slope indicates that pain levels did not systematically change over time in a consistent way across participants. Variance estimates for momentary pain scores indicated significant between-participant variability at baseline. Estimates ranged from 0.43 to 1.76, suggesting that while some participants reported relatively stable pain levels, others reported greater fluctuations. Most variance estimates were statistically significant at the $p < 0.01$ level.

Physical Activity. The individual LGCM for physical activity demonstrated acceptable to good model fit (scaled $\chi^2(23) = 22.76$, $p = 0.48$ [Yuan-Bentler correction], SRMR = 0.084, robust RMSEA = 0.000 [90% CI [0.000, 0.112]], robust CFI = 1.00, robust TLI = 1.00). The mean growth intercept for physical activity was significantly different from zero (214.65, SE = 10.53, $p < 0.001$) while the slope was not significantly different from zero (0.63, SE = 1.79, $p = 0.73$). The intercept indicates that, on average, participants initially engaged in "light" physical activity at baseline however the lack of significant slope indicates that physical activity levels did not systematically change over time in a consistent way across participants. Variance estimates for momentary physical activity indicated significant variability at baseline, indicating that some participants had more variation in their levels of physical activity than others. Estimates ranged from 3667.39 to 6092.34. All variance estimates were statistically significant at $p < 0.05$.

See **Table 3** and **Table 4** for model and variance estimates from individual LGCMs for pain and physical activity variables at baseline.

Table 3: Parameter Estimates from Pain and Physical Activity Individual LGCMs at Baseline

	Estimate	**SE**	**z-value**	**p-value**	**Std.lv/all**
Pain					
i_{pain}	5.60	0.21	26.77	< 0.001	3.05
s_{pain}	-0.02	0.02	-0.70	0.49	-0.12
$i_{pain} \sim\sim s_{pain}$	-0.05	0.05	-0.99	0.32	-0.20
Physical Activity					
i_{PA}	214.65	10.53	20.39	< 0.001	2.55
s_{PA}	0.63	1.79	0.35	0.73	0.08
$i_{PA} \sim\sim s_{PA}$	-158.17	248.02	-0.64	0.52	-0.25

Note. i = intercept such that i_{pain} represents the intercept of the pain variable. s = slope such that s_{pain} represents the intercept of the pain variable, ~~ represents correlation, PA = physical activity, SE = standard error, Std.lv/all = standardized latent variable/standardize all.

Table 4: Variance Estimates for Pain and Physical Activity Variables from Individual LGCM Models at Baseline

	Estimate	**SE**	**z-value**	**p-value**
Pain Model				
Rating 1	1.76	0.59	2.98	0.003
Rating 2	0.43	0.11	3.89	<0.001
Rating 3	1.34	0.81	1.65	0.10
Rating 4	0.51	0.17	3.02	0.003
Rating 5	0.53	0.12	4.31	<0.001
Rating 6	0.79	0.29	2.73	0.006
Rating 7	0.54	0.24	2.30	0.02
Intercept	3.37	0.60	5.60	<0.001
Slope	0.02	0.01	1.78	0.075
Physical Activity Model				
Rating 1	4039.29	1117.01	3.62	<0.001
Rating 2	5080.22	1063.25	4.78	<0.001
Rating 3	4623.74	1177.98	3.93	<0.001
Rating 4	4427.10	1117.65	3.96	<0.001
Rating 5	3667.39	725.53	5.06	<0.001
Rating 6	6092.34	1143.98	5.33	<0.001
Rating 7	5658.11	1700.50	3.33	0.001
Intercept	7106.20	1654.84	4.29	<0.001
Slope	56.58	75.45	0.75	0.45

Note. SE = standard error.

Baseline Parallel Growth Trajectories

The parallel LGCM for pain and physical activity at baseline demonstrated acceptable model fit (scaled $\chi^2(91) = 117.42$, $p = 0.03$ [Yuan-Bentler correction], SRMR = 0.062, robust RMSEA = 0.062 [90% CI [0.000, 0.099]], robust CFI = 0.97, robust TLI = 0.97).

Intercept- and Slope-Level Relationships. At baseline, the covariance between the intercepts of pain and physical activity was non-significant ($\hat{\psi} = -8.04$, SE = 21.16, $p = 0.704$ [$\hat{\psi}_{std} = -0.05$]; Figure 4, path A) indicating no observed relationship between participants' initial level of pain and initial amount of physical activity. The covariance between the slopes of pain and physical activity approached significance ($\hat{\psi} = -0.84$, SE = 0.46, $p = 0.07$ [$\hat{\psi}_{std} = -0.73$]; Figure 4, path D) with a negative relationship, indicating a trend towards an inverse relationship between changes in pain and physical activity over the baseline observation period.

Intercept-by-Slope-Level Relationships. The covariance between the intercept of pain and the slope of physical activity was non-significant ($\hat{\psi} = -4.33$, SE = 3.10, $p = 0.16$ [$\hat{\psi}_{std} = -0.30$]; Figure 4, path C). Similarly, the covariance between the intercept of physical activity and the slope of pain was non-significant ($\hat{\psi} = 4.99$, SE = 3.59, $p = 0.17$ [$\hat{\psi}_{std} = 0.40$]; Figure 4, path C). Together, this indicates that, on average, participants' initial pain was not related to change in physical activity and their initial physical activity was not related to change in pain over the baseline observation period.

Additional Relationships. The covariance between the intercept and slope of pain was non-significant ($\hat{\psi} = -0.05$, SE = 0.05, $p = 0.34$ [$\hat{\psi}_{std} = -0.183$]; Figure 4, path B). The covariance between the intercept and slope of physical activity was also non-significant ($\hat{\psi} = -160.13$, SE = 250.42, $p = 0.53$ [$\hat{\psi}_{std} = -0.243$]; Figure 4, path B). Together, this indicates that, on average, participants' initial pain was not associated with change in pain and their initial physical activity was not associated with change in physical activity over the baseline observation period.

See **Table 5** for model estimates from parallel LGCMs for pain and physical activity variables at baseline.

Table 5: Covariance Estimates and Standardized Coefficients from Parallel LGCM of Pain and Physical Activity at Baseline

	Estimate	SE	z-value	p-value	Std.lv/all
$i_{pain} \sim\sim i_{PA}$	-8.04	21.16	-0.38	0.70	-0.05
$s_{pain} \sim\sim s_{PA}$	-0.84	0.46	-1.83	0.07	-0.73
$i_{pain} \sim\sim s_{pain}$	-0.05	0.05	-0.96	0.34	-0.18
$i_{PA} \sim\sim s_{PA}$	-160.13	250.42	-0.64	0.52	-0.24
$i_{pain} \sim\sim s_{PA}$	-4.33	3.10	-1.40	0.16	-0.30
$s_{pain} \sim\sim i_{PA}$	4.99	3.59	1.34	0.17	0.40

Note. i = intercept such that i_{pain} represents the intercept of the pain variable. s = slope such that s_{pain} represents the intercept of the pain variable, ~~ represents correlation, PA = physical activity, SE = standard error, Std.lv/all = standardized latent variable/standardize all.

Aim 2: Examine the extent to which participation in cognitive behavioral intervention changes the real time dynamic relationships between pain and physical activity.

Post-Intervention Individual Growth Trajectories

Pain. The individual LGCM for pain demonstrated a significant scaled chi-square statistic, $\chi^2(23) = 44.68$, $p = 0.004$ and a robust RMSEA of 0.141 (90% CI [0.048, 0.218]), indicating a poor fit, with an SRMR of 0.067 , suggesting an acceptable fit, and robust CFI and TLI values of 0.95, indicating good model fit according to conventional thresholds. The mean growth intercept for pain was significantly different from zero (5.35, SE = 0.28, $p < 0.001$) while the slope was not significantly different from zero (-0.01, SE = 0.04, $p = 0.69$). The intercept suggests that, on average, participants initially reported a moderate level of pain at post-intervention however the lack of significant slope indicates that pain levels did not systematically change over time in a consistent way across participants. Similar to at baseline, variance estimates for momentary pain scores indicated significant between-participant variability at post-intervention. Estimates ranged from 0.31 to 1.19, suggesting that while some participants reported relatively stable pain levels, others reported greater fluctuations. Most variance estimates were statistically significant at the $p < 0.05$ level.

Physical Activity. The individual LGCM for physical activity demonstrated good to excellent model fit (scaled $\chi^2(24) = 31.60$, $p = 0.14$ [Yuan-Bentler correction], robust RMSEA = 0.028 [90% CI [0.000, 0.144]], robust CFI = 0.99, robust TLI = 0.99), thought the SRMR suggested poor model fit (SRMR = 0.156). The mean growth intercept for physical activity was significantly different from zero (223.68, SE = 10.19, $p < 0.001$) while the slope was not significantly different from zero (-0.05, SE = 1.57, $p = 0.98$). The intercept suggests that, on average, participants initially engaged in “light” physical activity at post-intervention however the lack of significant slope indicates that physical activity levels did not systematically change over time in a consistent way across participants. Variance estimates for momentary pain scores ranged from 2969.49 to 14079.81 at post-intervention, indicating that some participants had more variation in their level of physical activity than others. Most variance estimates were statistically significant at the $p < 0.01$ level.

See **Table 6** and **Table 7** for model and variance estimates from individual LGCMs for pain and physical activity variables at post-intervention.

Table 6: Parameter Estimates from Pain and Physical Activity Individual LGCMs at Post-Intervention

	Estimate	SE	z-value	p-value	Std.lv/all
Pain					
i_{pain}	5.35	0.28	19.36	< 0.001	2.67
s_{pain}	-0.01	0.04	-0.40	0.69	-0.07
$i_{pain} \sim\sim s_{pain}$	-0.13	0.09	-1.41	0.16	-0.32
Physical Activity					
i_{PA}	223.68	10.19	21.96	< 0.001	3.42
s_{PA}	-0.05	1.57	-0.03	0.98	-0.01
$i_{PA} \sim\sim s_{PA}$	117.30	201.80	0.58	0.56	0.23

Note. i = intercept such that i_{pain} represents the intercept of the pain variable. s = slope such that s_{pain} represents the intercept of the pain variable, ~~ represents correlation, PA = physical activity, SE = standard error, Std.lv/all = standardized latent variable/standardize all.

Table 7: Variance Estimates for Pain Variables from Individual LGCM Models at Post-Intervention

	Estimate	SE	z-value	p-value
Pain Model				
Rating 1	0.87	0.38	2.32	0.02
Rating 2	0.51	0.17	3.01	0.003
Rating 3	1.04	0.42	2.51	0.01
Rating 4	0.80	0.29	2.73	0.006
Rating 5	1.19	0.47	2.56	0.01
Rating 6	0.64	0.21	3.00	0.003
Rating 7	0.31	0.19	1.61	0.11
Intercept	4.03	0.68	5.99	<0.001
Slope	0.04	0.02	1.84	0.07
Physical Activity Model				
Rating 1	6184.30	2252.07	2.75	0.006
Rating 2	2969.49	900.70	3.30	0.001
Rating 3	5839.24	1332.92	4.38	<0.001
Rating 4	14079.81	8303.75	1.70	0.09
Rating 5	4084.80	924.95	4.42	<0.001
Rating 6	3635.20	1031.86	3.52	<0.001
Rating 7	6378.41	1961.59	3.25	0.001
Intercept	4276.49	1384.12	3.09	0.002
Slope	61.404			

Note. To allow the model to converge, the variance of the slope of physical activity was constrained to be equal to its variance at baseline; SE = standard error.

Post-Intervention Parallel Growth Trajectories

The parallel LGCM for pain and physical activity at post-intervention demonstrated poor model fit (scaled $\chi^2(92) = 155.41$, $p < 0.001$ [Yuan-Bentler correction], SRMR = 0.105, robust RMSEA = 0.104 [90% CI [0.060, 0.142]], robust CFI = 0.88, robust TLI = 0.88). However, the chi-square to degrees of freedom ratio is less than 2:1, which indicates empirically reasonable fit (Schermelleh-Engel et al., 2003; Tabachnick & Fidell, 2019; Widaman & Thompson, 2003). Additionally, literature suggests that insights can still be gained from models with suboptimal fit (Stone, 2021).

Intercept- and Slope-Level Relationships. Post-intervention, the covariance between the intercepts of pain and physical activity was non-significant ($\hat{\psi} = 16.46$, SE = 18.85, $p = 0.38$

[$\hat{\psi}_{\text{std}}$ = 0.13]; Figure 4, path A), indicating that, at post-intervention there was no observed relationship between participants' initial level of pain and initial amount of physical activity. The covariance between the slopes of pain and physical activity was also non-significant ($\hat{\psi}$ = -0.37, SE = 0.66, p = 0.58 [$\hat{\psi}_{\text{std}}$ = −0.23]; Figure 4, path D), indicating a lack of relationship between change in pain and change in physical activity across the post-intervention observation period, which differs from the negative relationship approaching significance at baseline.

Intercept-by-Slope-Level Relationships. The covariance between the intercept of pain and the slope of physical activity was non-significant ($\hat{\psi}$ = -3.10, SE = 4.74, p = 0.51 [$\hat{\psi}_{\text{std}}$ = -0.20]; Figure 4, path C). Similarly, the covariance between the intercept of physical activity and the slope of pain was non-significant ($\hat{\psi}$ = -2.09, SE = 2.39, p = 0.38 [$\hat{\psi}_{\text{std}}$ = -0.15]; Figure 4, path C). Together, this indicates that, on average, participants' initial pain was not related to change in physical activity and their initial physical activity was not related to change in pain over the post-intervention observation period.

Additional Relationships. The covariance between the intercept and slope of pain was non-significant ($\hat{\psi}$ = −0.13, SE = 0.09, p = 0.17 [$\hat{\psi}_{\text{std}}$ = −0.31]; Figure 4, path B). The covariance between the intercept and slope of physical activity was non-significant ($\hat{\psi}$ = 139.75, SE = 207.80, p = 0.50 [$\hat{\psi}_{\text{std}}$ = 0.27]; Figure 4, path B). Together, this indicates that, on average, participants' initial pain was not associated with change in pain and their initial physical activity was not associated with change in physical activity over the post-intervention observation period.

See **Table 8** for model estimates from parallel LGCMs for pain and physical activity variables at post-intervention.

Table 8: Covariance Estimates and Standardized Coefficients from Parallel LGCM of Pain and Physical Activity at Post-Intervention

	Estimate	SE	z-value	p-value	Std.lv/all
$i_{pain} \sim\sim i_{PA}$	16.46	18.85	0.87	0.38	0.13
$s_{pain} \sim\sim s_{PA}$	-0.37	0.66	-0.55	0.58	-0.23
$i_{pain} \sim\sim s_{pain}$	-0.13	0.09	-1.38	0.17	-0.31
$i_{PA} \sim\sim s_{PA}$	139.75	207.80	0.67	0.50	0.27
$i_{pain} \sim\sim s_{PA}$	-3.10	4.74	-0.65	0.51	-0.20
$s_{pain} \sim\sim i_{PA}$	-2.09	2.39	-0.88	0.38	-0.15

Note. i = intercept such that i_{pain} represents the intercept of the pain variable. s = slope such that s_{pain} represents the intercept of the pain variable, ~~ represents correlation, PA = physical activity, SE = standard error, Std.lv/all = standardized latent variable/standardize all.

Multiple Group Analysis

The Wald Test used to determine whether the covariance between the slopes of pain and physical activity (Figure 4, path D) was significantly different between baseline and post-intervention was not significant ($\chi^2(1) = 0.21$, $p = 0.65$), meaning that this parameter was not significantly different between baseline and post-intervention.

Post-Hoc Analyses

Given the lack of statistical evidence for a change in the relationship between the slopes of pain and physical activity across intervention timepoints identified in the primary analyses, post-hoc analyses were conducted to provide additional insights into these dynamic associations and to examine more granularly the relationships between pain and physical activity at the individual level from baseline to post-intervention. Given the current study was underpowered to conduct further LCGM or to divide the sample, these supplementary and descriptive approaches were utilized to explore the nuanced relationships that may have not been captured in the primary analyses. These analyses were aimed at gaining a deeper understanding of the patterns within the data, particularly in the context of individual differences, such as sex and pain acceptance.

Post-Hoc Methods

First, for each participant who had sufficient data at both baseline and post-intervention, the correlation between pain and physical activity at both timepoints was computed, as well as a change score reflecting the change in magnitude of this correlation from baseline to post-intervention. One participant's post-intervention data was excluded due to the lack of variability in pain scores leading to an uninterpretable correlation value, leaving a total of 52 participants for post-hoc analyses. Relationships between correlation change and both sex and group membership were examined using liner models. Pearson's Correlation Coefficient was used to examine the relationship between change in CPAQ score and both correlation change and absolute value of the correlation change.

Next, tertiles were created based on the effect size of each participant's correlation coefficient using Cohen's guidelines for a medium effect size (Cohen, 2013). The "negative" tertile included participants with a correlation less than or equal to -0.3 and was assigned a value of 1. The "neutral" tertile included participants with a correlation between -0.3 and +0.3 and was assigned a value of 2. The "positive" tertile included participants with a correlation greater than or equal to 0.3 and was assigned a value of 3. Tertile change scores were calculated by subtracting the baseline tertile value from the post-intervention tertile value to examine how many participants switched tertiles and in which direction. Given that analyses using the continuous correlation variables were conducted and analyses with categorical variables generally have reduced power, these tertiles were used descriptively only.

Finally, four participants who switched tertiles, one from each direction of change, were selected and individual plots were created to display their relationship between pain and physical activity across all 21 observations at both baseline and post-intervention. Participants' pain and physical activity variables were converted z-scores so that the two variables could be plotted on the same scale. Z-scores were standardized to each individual's values across both baseline and post-intervention timepoints.

Post-Hoc Results

Pain Acceptance. The average CPAQ score was 45.21 (SD = 15.85, range: 1-100) at baseline and 56.53 (SD = 17.00, range: 3-110) at post-intervention. From baseline to post-intervention, the mean CPAQ change was 10.34 (SD = 13.95, range: -30-56). The average CPAQ Pain Willingness subscale score was 17.72 (SD = 8.32, range: 0-40) at baseline and 21.40 (SD = 9.05, range: 3-49) at post-intervention. From baseline to post-intervention, the mean CPAQ Pain Willingness change was 3.85 (SD = 8.70, range: -15-42). The average CPAQ Activity Engagement subscale score was 27.48 (SD = 10.60, range: 1-60) at baseline and 35.12 (SD = 12.13, range: 0-62) at post-intervention. From baseline to post-intervention, the mean CPAQ Activity Engagement change was 6.48 (SD = 10.00, range: -23-29). Sensitivity analyses were conducted to examine the effect of removing the outlier participant who's CPAQ score decreased by 30 and no meaningful differences were observed.

Correlations. At baseline, the average correlation between pain and physical activity was 0.05 (SD = 0.29, range: -0.59-0.65). Post-intervention, the average correlation between pain and physical activity was 0.06 (SD = 0.34, range: -0.59-0.80]). The average change in correlation from baseline to post-intervention was 0.03 (SD = 0.34, range: -0.67-0.84]). Based on the results of linear models, sex ($p = 0.67$) and group membership ($p = 0.78$) did not predict correlation change. The relationship between baseline pain-physical activity correlation and baseline CPAQ total score was not significant (r = -0.15 p = 0.28). However, the relationship between the absolute value of the correlation change and both CPAQ total score change and Pain Willingness subscale change was marginally significant (*r* = 0.29, *p* = 0.07 and *r* = 0.29, *p* = 0.08, respectively). The relationship between correlation change and CPAQ Activity Engagement subscale change was not significant (*r* = 0.21, *p* = 0.19).

Tertiles. At baseline, 11 participants were in the negative tertile, 55 were in the neutral tertile, and 19 were in the positive tertile. Post-intervention, 9 participants were in the negative tertile, 36 in the neutral tertile, and 13 in the positive tertile. Of the 52 participants who had sufficient data at both baseline and post-intervention, 23 switched tertiles and 29 remained in the same tertile. Of note, no participants switched from the negative to positive tertile or vice versa. Five participants switched from the negative tertile to the neutral tertile, seven from neutral to negative, 7 from neutral to positive, and 4 from positive to neutral. See **Table 9** for a descriptive summary of treatment group and sex for participants with sufficient data to classify into tertiles based on correlation strength and determine change in tertile.

Table 9: Treatment Group and Sex for Participants with Sufficient Data to Classify into Tertiles Based on Correlation Strength and to Determine Change in Tertile

Tertile Switch	**Treatment Group**		**Sex**	
	AMP	CBT	Male	Female
Negative to Neutral (n = 5)	3	2	3	2
Neutral to Negative (n = 7)	2	5	4	3
Neutral to Positive (n = 7)	3	4	5	2
Positive to Neutral (n = 4)	3	1	3	1
No change (n = 29)	24	5	20	9
Total (n = 52)	35	17	34	17

Note. AMP = ACTing with mindfulness for pain, CBT = cognitive behavioral therapy. Tertiles were determined based on the effect size of each participant's correlation coefficient (less than or equal to -0.3 "Negative", between -0.3 and +0.3 "Neutral", greater than or equal to 0.3 "Positive").

Visual Examination of Individual Relationships

Negative to Neutral. Participant 20 was a 57-year-old male in the MAP group with a change in correlation of 0.38 (baseline: -0.39, post-intervention: -0.01). Change in pain was -1.14 (baseline: 6.00, post-intervention: 4.86). Change in physical activity was -56.64 (baseline: 240.23, post-intervention: 183.59). See **Figure 5.** Compared to baseline, pain and physical activity appear less variable and more steady post-intervention; both variables "flatten out" lower than at baseline.

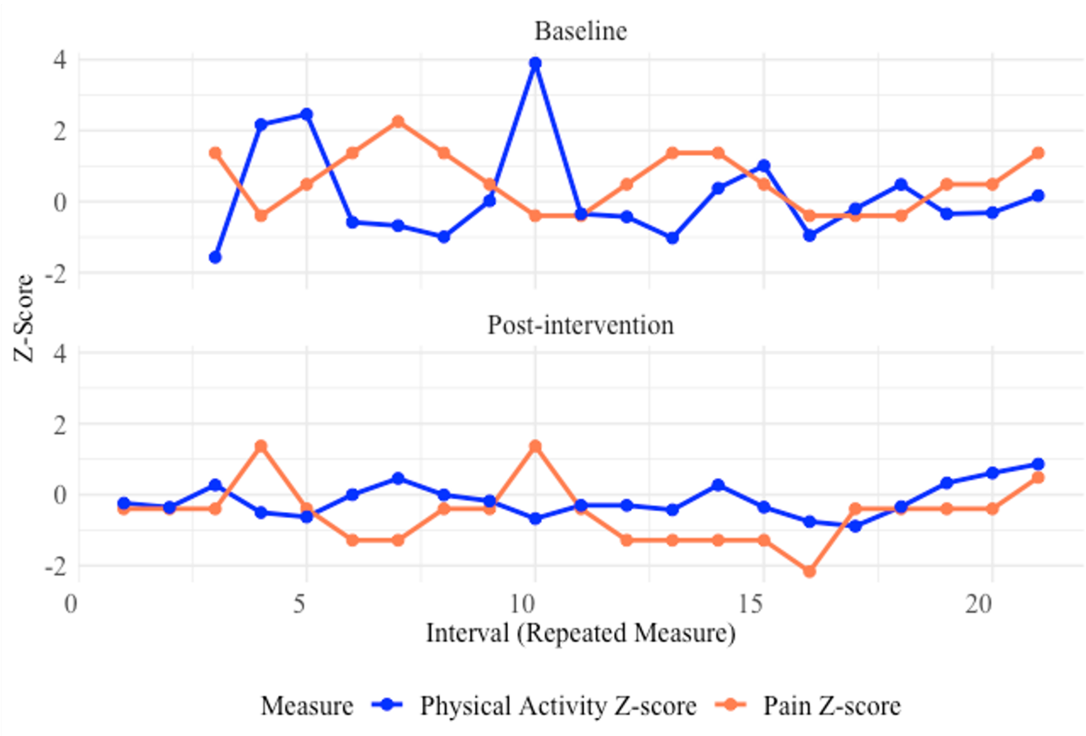

Figure 5: Standardize pain and physical activity for Participant 20. Z-scores standardized to the individual.

Neutral to Positive. Participant 1 was a 60-year-old female in the MAP group with a change in correlation of 0.50 (baseline: 0.02, post-intervention: 0.52). Change in pain was -4.91 (baseline: 5.65, post-intervention: 0.74). Change in physical activity was -11.2 (baseline: 169.89, post-intervention: 158.69). See **Figure 6**. Compared to baseline, this participant's pain ratings appear to have less variability and are lower at post-intervention while physical activity stayed roughly the same.

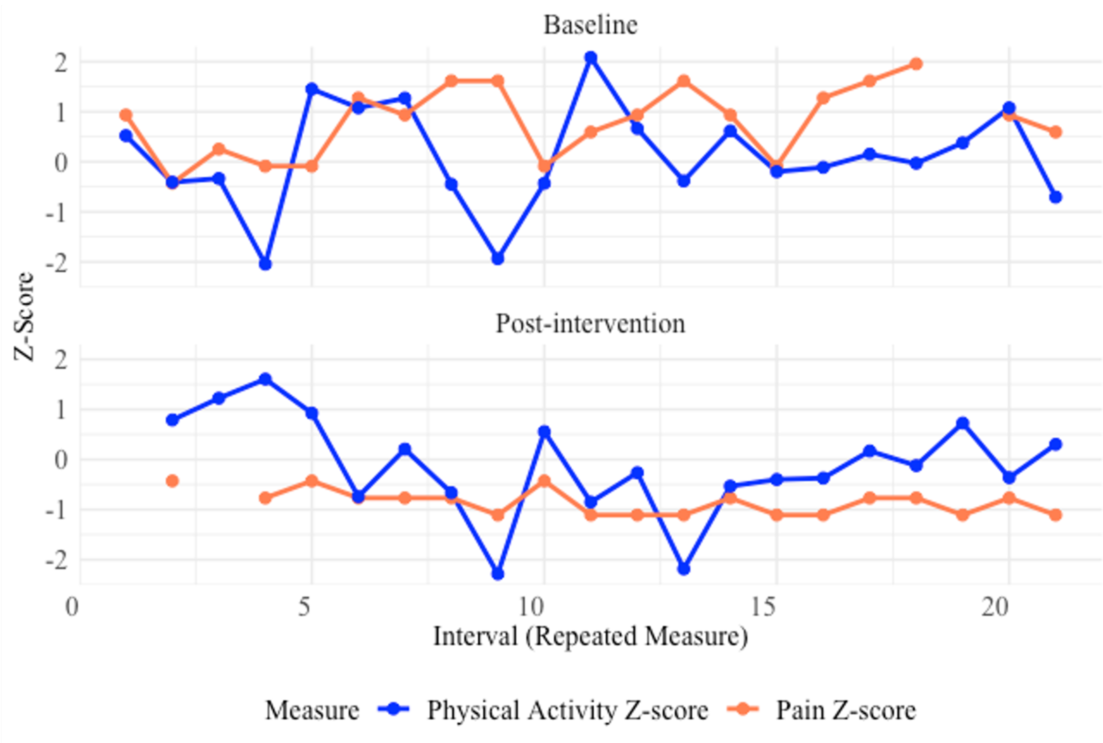

Figure 6: Standardize pain and physical activity for Participant 1**.** Z-scores standardized to the individual.

Positive to Neutral. Participant 6 was a 54-year-old male in the MAP group with a change in correlation of -0.49 (baseline: +0.35, post-intervention: -0.13). Change in pain was -4.78 (baseline: 7.58, post-intervention: 2.80). Change in physical activity was 13.03 (baseline: 131.37, post-intervention: 144.40). See **Figure 7**. Compared to baseline, pain decreased for the post-intervention observation period, however the timepoints in the middle of the post-intervention observation period (roughly intervals 9-14) exhibited a notably negative relationship, perhaps influencing the weakening of the overall correlation from positive to neutral.

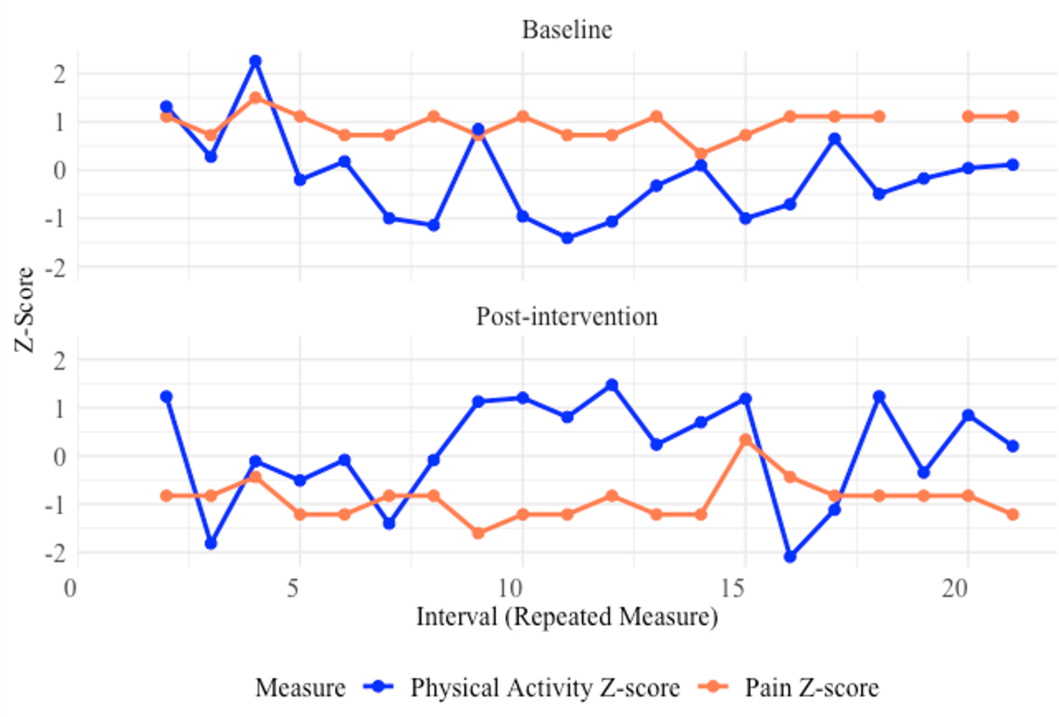

Figure 7: Standardize pain and physical activity for Participant 6. Z-scores standardized to the individual.

Neutral to Negative. Participant 48 was a 64-year-old female in the CBT group with a change in correlation of -0.44 (baseline: -0.11, post-intervention: -0.54). Change in pain was 0.24 (baseline: 3.33, post-intervention: 3.57). Change in physical activity was 5.23 (baseline: 140.93, post-intervention: 146.16). See **Figure 8**. At baseline, this participant had both instances of positively and negatively correlated pain and physical activity, leading to an overall weak correlation between the two variables. In comparison, at post-intervention, this participant exhibits a negative relationship whereby they have lower pain and higher physical activity at the beginning of the post-intervention observation period (roughly intervals 1-10) which switches to higher pain with lower physical activity in the latter half of the post-intervention observation period (intervals 11-21).

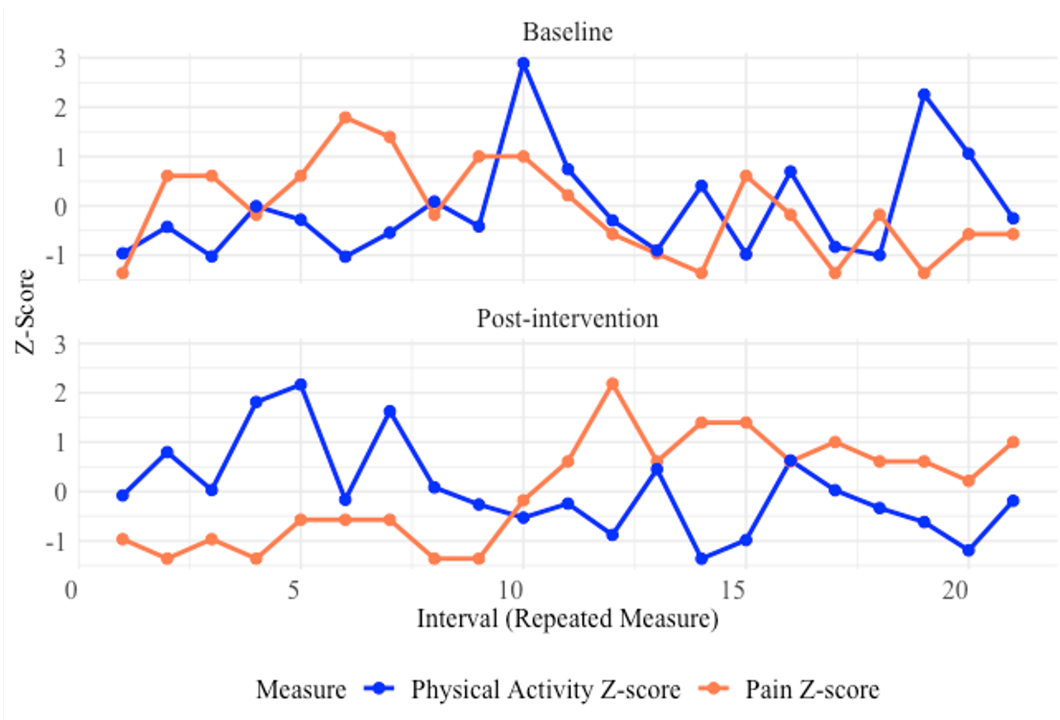

Figure 8: Standardize pain and physical activity for Participant 48. Z-scores standardized to the individual.

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Exploratory Aim: Qualitatively explore perceived factors driving the effect of intervention on function using thematic analysis.

Participants (*N* = 15) were 87% male (*n* = 13), 7 in AMP and 8 in CBT group. Contact was attempted with 22 potential participants. Related to the research aim of qualitatively exploring perceived factors driving the effect of intervention on function, the following four themes and 11 sub-themes emerged: Pain Acceptance (subthemes: *accepting limitations*, *pain permanence*, and *thoughts*), Activity Pacing (subthemes*: activity paced on pain*, *breaking up a task*, and *planning ahead*), Change (subthemes: *change in activity*, *no/unclear change*), and Pain-Physical Activity Relationship (subthemes: *activity despite pain*, *activity to manage pain*, and *pain modifies activity*). Each theme and sub-theme are described, and illustrative quotations are included below.

Pain Acceptance

More than two thirds of the participants (n = 11) discussed acceptance in relation to their pain. Within the theme of Pain Acceptance, sub-themes of *accepting limitations, pain permanence,* and *thoughts* were identified.

Accepting limitations. Some participants reported awareness and acceptance of the reality that they have limitations due to their pain. This included physical limitations. For example, Participant 89 stated: "Certain pains will not allow me to do certain things […] for example, my back hurt, my ankle hurts […] physically I'm not going to do certain things because I know this is in pain and it hurts." However, this sub-theme also included communication with family members about such limitations to physical activity, family engagement, and emotion regulation. For example, Participant 109 reported:

> [Pain is] still more a limiting factor to certain things I do, but also, I realized that it's like all the skills you learned to be able to communicate with people what's

going on. Uh. Also, just understanding that "Hey, I do have limitations but there's a way that I can do things without harming myself more because I have those limitations. But then also know that because I have limitations, it doesn't mean that I can't do things. It just takes longer." And it's accepting that. Um. Even now, being 50 years old, it's now accepting that yea there's things I can't do because of pain.

This some participant also discussed communicating about his limitations at work:

[…] and even at work it helps me too because I can relay it now to "Hey guys. I am having back pain today. I can't make it in because this is- I'm having problems with my back." Uh. Or even to the point where this depression- there was a period I actually- I went through a week where I told my boss, I go "Hey, I'm having mental depression stuff, I need to take a mental break. I need to, you know, be off work or if you can let me work from home this week, I would appreciate it." You know, the class would give courage to actually ask for what I want. You know, 'cause again it's up to my boss to say yes or no and do it and I know how to respond to that either way. But it's just being able to be up front with people about what's going on with me and allow the chips to fall wherever they are.

Pain Permanence. Some participants described the intervention helping them to accept that pain is something that will always be present for them, allowing them to stop fighting against it. For example, Participant 121 stated: "[…] I guess the biggest thing is… I don't question it as much as anymore. […] I just know it's, uhm, I don't question like "Why am I always in pain" I just now know that, yeah, I'm just gonna be in pain." While Participant 89 stated, "The pain that I do have, I live with. That's not going to go away."

Thoughts. Some participants described the intervention altering how they respond to or think about pain and its role in their lives. In realizing that they are separate from their pain and from their thoughts about pain, they can change how they relate to these thoughts and experiences of pain. For example, Participant 109 said: "I understand I still have the same pain but it's just navigating through it allows me a better life. It's how I respond to it, how I react to it, how I treat it. Because now I am able to manage it better than I was able to before." While another Participant 119 stated: "I respond to my pain without being mad or agitated, I just kind of live with it and deal with it and not make it bring me down so that others around me are as- are not down or look at me "Oh there's [John], he's got a problem. He's probably gonna be fussy or aggravated about it." No, I don't let my misery, uhm, love company if you will."

Activity Pacing

More than one third of the participants (n = 6) reported using some variation of activity pacing, which, in the chronic pain literature includes strategies aimed at modifying activities to reduce fluctuations from high to low activity levels and improve function (Andrews et al., 2012; Antcliff et al., 2018). Activity pacing can include taking frequent short rests and splitting tasks up. Within the theme of Activity Pacing, sub-themes of *activity paced on pain, breaking up a task,* and *planning ahead* were identified.

Activity paced on pain. Some participants described generally altering the rate or amount of their activity based on their pain level in the moment as opposed to planning ahead or breaking up a task. For example, Participant 95 said: "In my life I don't want to be just sitting doing nothing that's not much of a life. I just need to do it based on the pain." Similarly, Participant 106 stated, "I know that I cannot do complete ultimate- ultimate activity, so I, I tend to put a measurement on what I can do. Yeah, so as soon as I feel pain, I usually stop at that point." The same participant later stated, "If I feel pain, I stop what I'm doing, uh, I usually sit down if possible. And if I'm at home, I usually lay down. Lay down on the couch or lay down on the bed, rest a while, and then get up and continue on, yeah."

Breaking up a task. Participants also described breaking up a larger task into parts as opposed to trying to complete the task in its entirety. Accordingly, Participant 106 described: "Instead of trying to do, like, I walk every day, like I mentioned during the uh, group therapy. Instead of doing a straight thirty-minute walk, which is, uh, sometimes unbearable, without help of medication, So I know how to pace myself… and I actually found a path that has chairs or has a place that you can sit by a tree and wait a while before you continue walking. And that really helps." Similarly, Participant 109 described breaking up the task of unpacking boxes:

> We had a lot of stuff at our house from when we moved and there's a lot of stuff in the garage from when we moved. And you look at it and it's just overwhelming and you go "Oh my gosh. My back's hurting. I don't wanna do this. My knee's hurting. And I'm having pain. I really don't wanna do this." So I go, you know what Imma do. I'm just gonna do a little bit at a time. And so I go, "You know what if I can get two boxes today I'll get two boxes." So I got the two boxes one day, got another couple of boxes the next day, and continue on and before you know it, "Wow! After about two weeks, I got results." It took two weeks to do smalls things. You know. So, I'm managing my pain rather than trying to "He-Man it" and do all this in one day. I took a little at a time and managed what I could because I do know that the more I look at things the more overwhelmed you get, but then when you start chipping at things and see progress, the better you feel about it. And you do make progress because it's just a little bit at a time, but you make the progress, and then you get- I don't stress myself out. I don't- 'course when you stress, pain comes up. So just by doing that, I'm actually able to handle a lot more and I get to reward myself by jumping in the jacuzzi or the pool.

Planning ahead. Some participants reported thinking ahead about how much activity they think they will be able to handle and altering their plans accordingly. This included limiting their activity before an event that they wanted to prioritize, for example Participant 107 said: "Well yes and I do, especially if I'm gonna pace myself I know, I know, like if I know something is coming up, especially an outside activity where I have to go somewhere and drive, Um I will not do something that I feel is just unnecessary you know before I do that so I have the time and energy to go do the other activity that I need to go to." This also included ordering tasks such that more effortful tasks get completed first such as in the example given by Participant 118:

> I give myself chores, right. Cause some days I don't work, my wife is at work, and uh, there's chores to be done. So, I'll do the vacuuming, knowing that I have to vacuum, I have to do the dishes, I have to cook dinner. So, if I could do the vacuuming first, that's the most physically hard one, so I'll do that one first to get it out of the way, then I could rest. Then I could do dishes, and then I could rest. And then I could make dinner.

Change

All 15 participants reported on their perceptions of change, or lack thereof, in activity or skill use and were specifically asked to reflect on their change since the intervention. Within this theme, sub-themes of *change in activity* (i.e., new activity, more activity) and *no/unclear change* emerged.

Change in activity. Many participants reported either engaging in more activity or new activities since the intervention. For example, Participant 114 described engaging more in pre-existing family activities: “I would say yes it has changed since the group because again, uh, I don’t uh, because family is here, I, I, I do find myself trying to be a part of what’s going on rather than prior to uhm, me learning about meditation and or the group, I wouldn’t participate at all.” While Participant 106 described a new activity he started doing: “Uh, I think most of the activity now, is, or was, focused on what I heard. Uh, like, going to community center, at which I have done. And for I’ve found a good walking uh, walking track that I walk with some of my buddies. Uh, I think they all came from the, from what I heard during the uh, during the uh, during the group session.”

No/unclear change. However, several participants also spoke of ambivalence or not noticing a change in their activity or skill use in the context of the intervention. Participant 121 stated: “Uh, I would really say [my amount of activity] hasn’t changed that much. Or if any at all. I think it’s pretty much has been the same, it’s just that I take some of the… helpful tips, uh helpful tips, that I got during the session and just try to implement them as I go about my non-working life.” Similarly, Participant 119 said: “I was already doing [activity pacing] before the program. I- A lot of the stuff I was already doing as, as, for, for who I am. Um, so I don’t really see that as something that improved upon, I told that to [the therapist] and the other veterans, I do that anyway 'cause we have, we have to know our limitations. So, did it help me with more activity? Um, no, not really."

Pain-Physical Activity Relationship

Most participants reported on their perceived relationship between pain and physical activity as they were explicitly asked to reflect on this relationship. Within this theme, sub-themes of *activity despite pain, activity to manage pain,* and *pain modifying activity* were identified.

Activity despite pain. Participants described engaging in activity despite the presence of pain. For example, Participant 95 stated: "If I want to get something done I just got to push try to ignore it." Similarly, Participant 117 stated: "[...] I know the the limitation of the pain, you know, I gotta finish something and it's gonna be a little painful, I just, I, I know it is, I just, deal with it, or I go find some Tylenol or ibuprofen, or, I mean, just, I guess, know my, know my limitations."

Activity to manage pain. Some participants reported activity helping lessen their pain or improve their pain management. Participant 109 said: "[Physical activity] has a positive influence because it keeps the joints moving so there's less time for it to stiffen up and actually have the pain. The other aspect to is that when I'm physically moving I'm actually burning calories and that helps me manage my weight better too." Similarly, Participant 106 stated: "I actually accepted the fact that I do have pain. And [...] I think it's controllable with medication or maybe with exercise, and also some things, [...] I think the most valuable on mine is [...] medication and then exercise, and physical therapy."

Pain modifies activity. Conversely, some participants described their pain levels limiting their amount of activity. For example, Participant 103 stated: "Yes [...] it limits the amount so if I know [...] that I was going to go to a game at Petco park just kinda doing the math in my head how much walking I'll be doing around depending on the level of pain is whether I'll be able to do it or not [...] if I have to walk let's say an average of 2-3 miles I don't know if I can do 3 miles today." Similarly, Participant 90 said: "I would love to play basketball, but I can't because the pain [...] just limits me from doing a lot of physical work right, if I wanted to go workout I can't lift weights or anything like that, so I have to reduce myself to swim and that's hard for me to get motivated to swim [...] and exercise."

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Discussion

This dissertation aimed to 1) characterize the real-time, dynamic relationship between pain and physical activity, 2) examine the extent to which these real-time dynamic relationships between pain and physical activity change in the context of participation in cognitive behavioral intervention, and 3) qualitatively explore perceived factors driving the effect of intervention on participants' relationship with pain. These aims were examined in a sample of Veterans with heterogenous chronic pain participating in eight weeks of virtual group cognitive behavioral intervention for chronic pain (AMP or CBT). Therefore, this research was designed to contribute to the evidence base of the understanding and treatment of chronic pain by enhancing the understanding of the relationship between pain and physical activity.

Primary Aims

Aim 1

At baseline, there was a negative relationship between the slopes of pain and physical activity that approached significance, partially supporting the hypothesis for Aim 1. This suggests that as pain levels increased, physical activity decreased and vice versa. This would be consistent with a pattern where worsening pain is associated with activity avoidance or conversely where increasing activity is associated with pain relief. These findings align with prior research suggesting that the relationship between pain and physical activity is complex and potentially bidirectional (Alzahrani et al., 2019; Pan et al., 2019; Tynan et al., 2023; Wang et al., 2025). For example, while some studies have found that physical activity is a beneficial strategy for pain management (Ambrose & Golightly, 2015; Shiri & Falah-Hassani, 2017), other studies show that individuals with chronic pain may engage in activity avoidance or experience exacerbations of pain symptoms associated with physical activity (Kroska, 2016; Øverås et al., 2020). Importantly, a prior study found that individuals with chronic pain who had not undergone intervention experienced a similarly negative relationship between pain and physical activity when pain acceptance was low (Kratz et al., 2017). Given the current results were observed at baseline, pain acceptance would be expected to be lower than at post-intervention, which could implicate pain acceptance as a potential mechanism influencing the direction and strength of the pain-physical activity relationship prior to intervention.

All other intercept-slope and intercept-intercept relationships were non-significant at baseline, suggesting that initial levels and changes in pain and physical activity were not strongly or systematically related at the group level. Initial pain levels were not predictive of how pain changed over the observation period. This indicates that individuals with higher initial pain did not necessarily experience greater increases or decreases in pain over the observation period. Similarly, initial activity level was not predictive of how physical activity changed over the observation period. Thus, individuals with higher initial physical activity did not necessarily experience greater increases or decreases in physical activity over the observation period.

Individuals with higher initial pain levels did not consistently have higher or lower initial physical activity. This could mean that initial pain was not a strong determinant of initial physical activity, which indicates that other factors that vary across individuals (e.g., external constraints, motivation) may play a larger role in shaping these factors, further highlighting the need for more individualized consideration of the variables uniquely impacting individuals. Initial physical activity level was not predictive of how pain changed over the observation period. This means that individuals with higher initial physical activity did not necessarily experience greater increases or decreases in pain over the observation period.

Aim 2

At post-intervention, there was no longer evidence for a trend between the rates of change of pain and physical activity and there was no evidence for changes in the remaining intercept-slope and intercept-intercept relationships from baseline to post-intervention. However, there was no statistical evidence for a change in the relationship between the rates of change of pain and physical activity from baseline to post-intervention - thus the hypothesis for Aim 2 was not supported. Given the modest sample size for the current analyses, it is possible there was insufficient power to detect a statistical effect and while this finding should be interpreted with caution, it is useful to consider what this change in relationship would mean. The change in the relationship between the rate of change in pain and physical activity could suggest that the initial association between pain and physical activity weakened from baseline to post-intervention, potentially due to intervention effects. This decoupling could mean that the relationship between the rates of change of pain and physical activity may be alterable by intervention and is in line with prior research that showed that cognitive behavioral intervention targets, such as levels of pain acceptance, are associated with differences in the impact of pain on physical activity and function (Kratz et al., 2017). More specifically, the change in this relationship may indicate that participants engaged in activity despite their experienced level of pain, which could be due to improvements in intervention targets including pain acceptance, present moment awareness, defusion, self-as-context, behavioral activation, and/or self-efficacy. Of note, across the entire sample, pain acceptance increased from baseline to post-intervention, providing further justification to continue to examine the role of pain acceptance in this context. Alternatively, the intervention could have influenced either levels of pain and/or physical activity, which would decoupled the initial relationship. However, average pain and physical activity levels did not change from baseline to post-intervention, which does not support the influence of changes in pain or physical activity at the group level. Notably, the variances for both pain and physical activity variables indicated significant between-person variability, meaning that, while some individuals exhibited relatively stable pain and physical activity across the observation periods, others had more fluctuation from one epoch to the next. While this could not be examined as a driving factor in the primary analyses, it indicates that these variables perform differently across individuals and thus provides further indication that group-level effects may not be the best-equipped method to examine these relationships.

Overall, the lack of strong cross-domain relationships indicates that, at the group level, pain and physical activity might be operating somewhat independently in this sample. However, some participants may have increased activity despite pain, while others may have reduced activity without noticeable pain improvements, leading to a "wash out" of any potential effect at the group level. However, there appears to be a trend such that the relationship between the rate of change of pain and physical activity weakens from baseline to post-intervention. Thus, closer examination of the dynamic changes in variables within individuals is warranted in post-hoc analyses.

Post-Hoc Analyses

Post-hoc analyses revealed wide variability in the magnitude of the relationship between pain and physical activity as well as in the magnitude of change in this relationship over the course of intervention. When examined at the individual level, participants' relationships ranged from strongly negative (e.g., r = -0.59) to strongly positive (e.g., r = 0.80) at both the baseline and post-intervention timepoints. While, at the group level, the was no systematic relationship observed between pain and physical activity, the post-hoc analyses reveal that, at the individual level, over one third of the participants exhibited a moderate positive or negative correlation (i.e., r < -0.30 or $r > 0.30$) between these two variables. Because these relationships were in opposing directions across individuals (i.e., some negative, some positive), this may have influenced the null finding found at the group-level effect. In addition, post-hoc analyses examining participants' change in the relationship between pain and physical activity over the course of intervention revealed highly variable change, indicating that, while some individuals exhibited a similar relationship between pain and physical activity both before and after intervention, almost one half of participants exhibited change in this relationship (i.e., an increase or decrease in strength of the relationship, reflected by changes in effect size classification). Thus, while the pain-physical activity relationship changed for many participants, it did not do so in a systematic way at the group-level.

Thus, the initial post-hoc analyses provide preliminary evidence that the relationship between pain and physical activity in Veterans with chronic pain can change over time in the context of a cognitive behavioral intervention, suggesting that this relationship may be alterable. This has several implications. First, it indicates that not all individuals are stuck in a fixed pattern of pain and physical activity and that larger datasets are warranted to understand the individual factors that determine changes in this relationship. In addition, these results encourage the future development and use of individualized modeling approaches to optimize the understanding and treatment of chronic pain. Second, acknowledging this relationship's alterability opens the door to further research aimed at identifying factors associated with more favorable changes. This, in turn, could inform the refinement of existing interventions and the development of new treatment approaches, while also contributing to a deeper understanding of the mechanisms through which behavioral treatments exert their effects. Understanding these factors would allow clinicians to tailor interventions to better support individual needs, either by enhancing components that facilitate positive change or addressing barriers that hinder it.

Post-hoc analyses also sought to preliminarily explore if any relevant variables may be associated with change in the pain-physical activity relationship from baseline to post-intervention. While sex could not be examined due to a lack of power, there was no evidence for treatment group (AMP vs. CBT) as being related to change in the relationship between pain and physical activity. However, there was a trend towards improvements in pain acceptance, and its sub-component of pain willingness, as being related to change in the relationship between pain and physical activity such that higher pain acceptance and pain willingness was related to change in the relationship between pain and physical activity. This is in line with prior research that has indicated that pain acceptance mediated the relationship between pain and physical activity, in that case, decoupling it (Kratz et al., 2017). Given the small sample size and the strong theoretical justification for examining treatment group, sex, and pain acceptance, the lack of effect in expected directions observed in the current study should not be assumed to rule out these factors. However, it does indicate that other factors should be additionally explored to determine which factors most influence the pain-physical activity relationship and its change.

Visual Examination of Individual Graphs

Visual examination of the graphs of four participants whose pain-physical activity relationship changed from baseline to post-intervention revealed diverse individual-level patterns that further highlight the variability in the relationship between pain and physical activity both across and even within participants.

For Participant 20, the visually observed pattern aligned with the hypothesized direction of change for the primary analyses: from a negative association between pain and physical activity at baseline to a more neutral relationship post-intervention. In line with the primary hypotheses, the participant initially exhibited higher pain ratings associated with lower levels of physical activity, a pattern which may be consistent with pain avoidance. This trend was particularly evident early in the baseline observation period. Post-intervention, the relationship appeared to "decouple," with pain and activity levels becoming more independent, or less strongly related. However, this shift seemed to be driven by reduced variability in both pain and activity, resulting in flatter trajectories for each variable. Consequently, the observed neutral relationship may reflect a statistical product of reduced variance rather than a meaningful behavioral change. Given the overall decline in both pain intensity and variability, it is difficult to determine whether the participant would have continued to exhibit a negative association had higher pain levels occurred.

For Participant 1, the correlations alone suggest a “coupling” pattern in which higher pain ratings are associated with higher levels of physical activity, which might imply physical activity contributing to increased pain (i.e., both pain and physical activity are relatively high). However, visual inspection of the graph indicates that the apparent change from a neutral to positive association may be driven by a reduction in variability in pain ratings, while physical activity levels remained relatively consistent across the observation period. In this context, the relationship could alternatively be interpreted as a form of “decoupling,” wherein physical activity varied independently of changes in pain. That is, despite fluctuations in physical activity, pain ratings remained largely unchanged, suggesting a weakening of the relationship between the two variables.

For Participant 6, the shift from a positive to a more neutral relationship between pain and physical activity appears to be primarily influenced by a distinct interval in the middle of the post-intervention observation period, during which there was a notably negative association characterized by low pain levels and high physical activity. Outside of this interval, the relationship between the two variables remained relatively neutral to weakly negative. Although this participant did not show an overall increase in average physical activity across the full observation period, they did exhibit an interval in which physical activity exceeded one standard deviation above their own average during the period of lower pain, which was not observed at baseline. This pattern may suggest that the overall reduction in pain allowed for brief periods of increased physical activity, even in the absence of a broader trend.

For Participant 48, the relationship between pain and physical activity became negatively coupled at post-intervention, consistent with a pattern of pain interference (i.e., physical activity was low when pain was high). This trend opposes the hypothesized decoupling effect of intervention and may represent an individual whose data offsets any overall group-level effect. This raises the possibility that certain participant characteristics, such as intervention group, sex, or within-person variability, may contribute to this specific pattern, though the current study is not powered to explore such moderators. Nevertheless, in a clinical context, this participant's data may be particularly valuable in that it prompts important questions such as: Why does this individual appear to worsen? Do they subjectively perceive themselves as worsening? Could this change be related to the intervention, contextual life factors, or even methodological issues in data collection? For example, it would be helpful to be able to ascertain if an event occurred midway through the observation period that may have triggered an increase in pain and a corresponding reduction in physical activity.

Based on visual examinations of the individual-level data, no consistent pattern emerged to explain shifts in the pain–physical activity relationship in a predictable direction, either toward greater decoupling (e.g., negative to neutral or positive to neutral) or increased coupling (e.g., neutral to negative or neutral to positive). Among the two participants whose data became more coupled from baseline to post-intervention, both demonstrated periods of both positively and negatively correlated pain and physical activity at baseline, resulting in an overall weak or neutral baseline association. However, their post-intervention patterns diverged: for one participant, the relationship became more negative primarily due to a flattening of the pain trajectory, while the other exhibited a classic pattern of pain interference, with a distinct period of low pain and high physical activity followed by high pain and low activity.

Taken together, visual inspection of these individual graphs revealed that the relationship between pain and physical activity shifted in each of the four possible directions from baseline to post-intervention. This variability offers insight into the absence of significant group-level effects in the primary analyses. Although pain, averaged across the 7-day observation period, did not significantly change across the full sample, three of the four participants demonstrated a reduction in average pain of at least one point on the 1–10 scale with two of the participants demonstrating a clinical meaningful reduction in pain of at least 30% (Laigaard et al., 2021). Notably, this reduction did not consistently correspond with either a strengthening or weakening of the pain–physical activity relationship, suggesting that for some individuals, lower pain may contribute to changes in the relationship, whereas for others, it may not. Importantly, both interventions focus on improving one's ability to function despite ongoing pain. Nonetheless, previous research has found that cognitive behavioral interventions can be associated with reductions in reported pain intensity (Knoerl et al., 2016) and some traditional CBT methods (e.g., diaphragmatic breathing, guided imagery, cognitive restructuring) do intend to decrease the experience of pain (Stewart et al., 2015). In the current sample, however, pain intensity did not significantly differ from baseline to post-intervention at the group level, indicating that these interventions did not uniformly affect pain levels across participants.

In contrast to the patterns observed in pain, but consistent with the full sample, average physical activity levels remained relatively stable from baseline to post-intervention for the four participants whose data were visually examined. Therefore, individual-level changes in average physical activity do not appear to explain the shifts in the pain–physical activity relationship. However, there were specific periods within the observation windows in which physical activity may have contributed to changes in this relationship. Important, neither the AMP nor CBT intervention was designed to explicitly increase physical activity. Rather, both interventions target mechanisms (e.g., pain acceptance and activity pacing, respectively) that are theorized to help individuals improve daily functioning despite the presence of pain. While these mechanisms could theoretically decouple the relationship between pain and physical activity by encouraging activity regardless of the presence of pain, the current analyses do not provide clear evidence supporting this. Previous studies have observed consistent changes in physical activity following cognitive behavioral interventions only if that intervention also targeted physical activity (Black et al., 2024; Heapy et al., 2021; VanBuskirk et al., 2014), suggesting that further research is needed to determine under what circumstances such interventions may influence physical activity behavior outside of explicit physical activity interventions.

Exploratory Qualitative Aim

The purpose of exploring themes in the qualitative data was to better understand individuals' experience of the dynamic relationship between pain and physical activity in the context of cognitive behavioral chronic pain intervention, ultimately leading to the refinement and improvement of cognitive behavioral interventions for pain and other chronic conditions. As expected, several themes aligned with the theoretical foundations of the interventions, such as Pain Acceptance (targeted in the AMP intervention) and Activity Pacing (targeted in the CBT intervention). Additional themes emerged in response to exploratory questions that asked participants to reflect on their relationship between pain and physical activity, as well as perceived changes over time.

Importantly, within these anticipated themes, sub-themes revealed variation in how participants experienced and applied these concepts. For example, under the theme of *Change*, there was a clear bifurcation: about half of described noticeable change or improvement in their level of activity or in their relationship between pain and physical activity, while others stated uncertainty or felt that no change occurred. Similarly, within the *Pain-Physical Activity Relationship* theme, participants reported using the intervention skills in diverse ways: some engaged in activity despite pain, others felt physical activity reduced their pain, and some limited physical activity in response to pain.

This heterogeneity mimics the results of the quantitative results; participants experienced the pain-physical activity relationship in distinct, individualized ways that did not follow a consistent pattern across the sample. For example, one participant may describe limiting physical activity due to pain as functional improvement while another may feel equally positive about persisting in activity despite pain. Though both may subjectively report improvement, their quantitative data would likely appear quite different and could effectively "cancel out" in group-level analyses such as those discussed prior. Moreover, several participants endorsed multiple sub-themes within the same theme, meaning that the pain–physical activity relationship may vary not only between individuals but also within individuals across days or even epochs, again contributing to the absence of clear patterns in the quantitative data.

Particularly interesting to contextualize in the current dissertation is the *thoughts* sub-theme under the Pain Acceptance theme. Within this sub-theme, participants discussed their relationship with pain from a metacognitive lens. Participants endorsed realizing that they have agency in how they respond to their pain or thoughts about their pain. They appeared to notice that they are separate from their experience of their pain and thereby have the choice in how to react to it. This concept aligns with both the CBT skill of challenging interfering behaviors and beliefs as well as the ACT concept of self-as-context which encourages individuals to develop awareness of the observing self, separate from the content of their thoughts (Hayes et al., 2006). As one of the six key processes in ACT, self-as-context is intended to detach individuals from more rigid identities based around pain or other struggles and become more present-focused and accepting and thereby has great potential to improve perceived functioning in chronic pain patients. The participants who endorsed this sub-theme in the current dissertation reported perceived benefit from this aspect of their relationship with pain. However, this mechanism would be difficult to capture quantitatively as reacting with more awareness and acceptance of one's pain may not necessarily lead to an increase in physical activity consistently. Thus, this sub-theme represents a perceived intervention-related benefit that likely was not captured in the quantitative data.

Implications and Future Research

This results of this dissertation have implications for both research and clinical work.

Research Implications

The current findings represent an initial step toward understanding the highly individual and dynamic relationship between pain and physical activity and provide a potential explanation for prior inconsistencies in the literature (Tynan et al., 2023). Based on the current results, the research implications have two foci. First, *mechanistic approaches* are needed to better understand treatment moderators underlying changes in the pain-physical activity relationship over time. The current study was under-powered to examine moderators such as sex, treatment group, and treatment-related changes in pain acceptance, however there was a trend towards improvements in pain acceptance being related to change in the pain-physical activity relationship. Future studies should be designed with sufficient power to test these and other theoretically relevant moderators (e.g., psychological flexibility, pain catastrophizing, pain condition) which could help explain why this relationship varies across individuals and inform the refinement and tailoring of interventions to specific patient needs. Second, this dissertation's findings contribute to a growing body of research advocating for *idiographic approaches* to the understanding and treatment of chronic pain. The primary aims identified an overall lack of group-level effects in both the pain-physical activity relationship and its change over time. However post-hoc analyses revealed that this apparent lack of effect masked substantial inter-individual variability that did not follow a consistent or predictable pattern at the group level. This was further highlighted in qualitative findings that revealed the wide range of subjective experiences reported by individual participants regarding engagement with skill use and perceived benefit. Together, these findings highlight the limitations of traditional nomothetic approaches that focus on group-level commonalities or patterns. While nomothetic approaches are useful in examining average treatment effects, they neglect important individual differences in the experience and trajectory of chronic pain. Idiographic methods on the other hand, such as dynamic structural equation modelling and time-series modeling, are better suited to capture individualized patterns of pain and physical activity as well as contextual influences that may be obscured in aggregate data (Fisher et al., 2018; Hayes et al., 2022). Future research using idiographic methods will serve to advance precision behavioral health and improve outcomes for the heterogenous chronic pain population.

In line with this personalized approach, future research using EMA would benefit from capturing contextual information alongside pain and activity ratings. Changes in the pain-physical activity relationship may be influenced by factors not measured in the current study (e.g., psychosocial stressors, pain flares, or engagement with intervention materials) and may occur across days or epochs. Including such data in future studies would allow for a richer understanding of what drives changes in the pain-physical activity relationship within individuals on a day-to-day basis in addition to over intervention.

While the current study integrated both quantitative statistical modelling and qualitative methods to examine change in the pain-physical activity relationship, it was not designed as a mixed methods study, and participants contributing qualitative data did not always have complete quantitative data. Future research should prioritize a fully integrated mixed methods design to more effectively link subjective experience with objective change, as both approaches offer complementary insights into functional outcomes in chronic pain.

Clinical Implications

The current quantitative and qualitative results revealed wide individual differences in the pain-physical activity relationship at baseline and post-intervention, and in the change of this relationship from baseline to post-intervention. These findings point to a need for more person-centered interventional approaches that are tailored to the unique experiences, behaviors, and psychosocial contexts of individuals with chronic pain. Therefore, clinicians can be confident that no two patients in their care are likely to exhibit the same relationship, nor respond to intervention in the same way. Patients can be expected to interpret and adapt treatment concepts to their own context and preferences, reinforcing the need for flexibility within treatment fidelity, as there are multiple valid ways to apply intervention skills and perceive benefit. Clinicians can use this knowledge to educate patients on the intended processes targeted in cognitive behavioral interventions and collaboratively set expectations for what change might look like in their experience of pain.

These findings align with emerging models of process-based therapy (PBT) which emphasize targeting core biopsychosocial processes (e.g., pain acceptance) rather than strictly adhering to a specific treatment protocol (McCracken, 2024). In PBT, interventions are selected based on an individual's specific needs and patterns, allowing for more precise and personalized treatment. PBT supports clinicians and patients working together to define meaningful markers of success and improvement. This could include identifying and tracking process-based progress goals like functional gains or increased psychological flexibility. In the future, it will be important to find out if perceived skill use, change, and functional improvement map onto increases in health outcomes or quality of life and to determine whether certain applications of intervention strategies are more effective for specific individuals or characteristics, ultimately advancing personalized care for the heterogeneous chronic pain population.

Limitations

The current study is not without limitations. First, LGCMs were used to address the quantitative aims. While these models are apt for examining overall trajectories and relationships between pain and physical activity, these models do not capture autoregressive or cross-lagged dynamics, limiting the ability to assess temporal or causal relationships between variables across time points. Therefore, the current study was not able to draw conclusions about how changes in one variable may influence the other from one epoch to the next. Second, while this study was designed to be adequately powered to examine its primary aims, it lacked sufficient power to explore potential moderators. This limits insight into what factors may explain individual differences in the pain-physical activity relationship. Third, the parallel LGCM at the post-intervention timepoint demonstrated poor model fit. This may be attributable to limited sample size or model misspecification; however, adding parameters would have introduced complexity not theoretically justified and was therefore not pursued. Fourth, this study was not designed as a mixed methods project. Although the integration of the quantitative and qualitative findings provided meaningful insights, a fully mixed methods approach would have allowed for deeper connections between participants' subjective experiences and quantitative patterns. Fifth, the qualitative methodology for the exploratory aim is inherently subjective. Although the PI was not part of the facilitation of either the AMP or CBT intervention, participant responses to the interview may have been biased towards providing positive or intervention-consistent responses. Additionally, the questions were designed to elicited information pertaining to the specific research question and therefore may have caused participants to report more information pertaining to their relationship with pain than they would have organically.

Conclusion

Chronic pain is a pervasive and disruptive chronic condition that afflicts a large and increasing number of people, especially Veterans (Rikard et al., 2023; Zelaya et al., 2020). Individuals with chronic pain experience a host of negative impacts including impaired functioning, poorer mental health and quality of life, and more comorbid conditions (Cohen et al., 2021; Johnston & Huckins, 2022; Mills et al., 2019) and have few effective treatment options (Cohen et al., 2021; Mattocks et al., 2020). Cognitive behavioral treatments, such as ACT and CBT offer a promising avenue of treatment that focus on improving one's function in the context of pain, and physical activity represents a useful metric to examine function. This dissertation demonstrated that the relationship between pain and physical activity is both dynamic and highly individualized in Veterans with chronic pain, and that these relationships may shift during cognitive behavioral interventions, even in the absence of consistent changes in pain intensity or physical activity. By utilizing ecologically valid methods like actigraphy and EMA, and integrating this with qualitative methods, this dissertation provides novel insight into the complexity of these relationships, has implications for both researchers and clinicians, and provides avenues for future research. Future work should build on the current findings by identifying mechanisms related to change in larger, more diverse samples and seeking to personalize interventions based on patient characteristics, ultimately leading to improved treatment for the host of individuals suffering with chronic pain.

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Appendix A

Table 10: Covariance Estimates and Standardized Coefficients from Non-Converged Parallel LGCM of Pain and Physical Activity at Post-Intervention

	Estimate	SE	z-value	p-value	Std.lv/all
i_{pain} ~~ i_{PA}	15.36	18.27	0.84	0.40	0.12
s_{pain} ~~ s_{PA}	-0.20	0.46	-0.41	0.68	-0.17
i_{pain} ~~ s_{pain}	-0.13	0.09	-1.40	0.16	-0.31
i_{PA} ~~ s_{PA}	259.55	147.05	1.77	0.08	0.74
i_{pain} ~~ s_{PA}	-2.40	3.36	-0.71	0.48	0.22
s_{pain} ~~ i_{PA}	-2.27	2.45	-0.93	0.36	-0.17

Note. i = intercept such that i_{pain} represents the intercept of the pain variable. s = slope such that s_{pain} represents the intercept of the pain variable, ~~ represents correlation, PA = physical activity, SE = standard error, Std.lv/all = standardized latent variable/standardize all.

Table 11: Variance Estimates from Non-Converged Parallel LGCM of Pain and Physical Activity at Post-Intervention

	Estimate	SE	z-value	p-value
Pain Variables				
Rating 1	0.86	0.39	2.21	0.03
Rating 2	0.51	0.17	3.00	<0.01
Rating 3	1.04	0.41	2.51	0.01
Rating 4	0.79	0.29	2.71	<0.01
Rating 5	1.18	0.47	2.53	0.01
Rating 6	0.65	0.21	3.03	<0.01
Rating 7	0.31	0.19	1.63	0.10
Intercept	4.02	0.67	5.98	<0.001
Slope	0.04	0.02	1.87	0.06
Physical Activity Variables				
Rating 1	7168.77	2279.37	3.15	<0.01
Rating 2	3057.76	866.65	3.53	<0.001
Rating 3	5856.92	1320.20	4.44	<0.001
Rating 4	14427.31	8385.30	1.72	0.09
Rating 5	4287.32	963.44	4.45	<0.001
Rating 6	4027.10	1135.01	3.55	<0.001
Rating 7	6346.35	1701.21	3.73	<0.001
Intercept	4061.71	1399.64	2.90	<0.01
Slope	-30.17	37.54	-0.80	0.42

Note. SE = standard error.

Appendix B

Interview guide for MAP group participants.

We're asking questions to better understand your experience since the intervention and to get Veteran feedback on how to improve it for future Veterans. What will be most helpful is your honest feedback, so please feel free to be honest about your experience- you won't offend me!

As a reminder, you participated in a group called **Mindful Action for Pain**. You attended virtual group sessions with **[Therapist Name]** back in **[date of group]**.

In this group, you practiced a lot of meditation, discussed pain acceptance, and worked on values and acting on your values, even while having pain. Does this sound familiar?

I know that the study was a while ago, so it's okay if you don't remember all the details or if you are unsure how to answer some of the questions. There are no right or wrong answers. **What we're really interested in is if and how this group has helped you to be more engaged in your life such as in exercising, socializing, and household tasks**. We are also looking for how to improve the intervention. Do you have any questions before we get started?"

1. What was the most helpful part of the group for your pain? For example, are there any skills or aspects of the group you remember that have helped you manage your pain?
2. What from the group did you feel was less helpful for your pain or could use improvement?
    - Prompt: What skills or aspects of the group do you remember that haven't helped you manage your pain?
3. When engaging in day-to-day activities now, how are you able to manage your pain?
4. What gets in the way of you managing your pain now?
5. What influence did the intervention have on your amount of activity including going on walks, getting out of the house, exercising, completing household chores, and spending time with friends or family?
    - Prompt: Are you doing more of these activity since the intervention? Less?
    - Prompt: Are you doing new or different kinds of activity?
    - Prompt: Does your pain influence how much activity you do now?
        - Prompt: How so?
6. I am now going to ask you about some specific topics covered in the group. Please tell me if and how you use each strategy to engage in more activities like getting out of the house, exercising, socializing, and completing household tasks when you have pain now?
    - Does meditation help you engage more in activities?
    - Does the idea of pain acceptance help you engage more in activities?
        - Prompt: In group, you discussed a metaphor of a Crying Baby on an Airplane, and the concept of "primary pain" and "secondary pain."
    - Does the idea of values help you engage more in activities?
        - Prompt: You may remember completing a worksheet that listed 10 different life domains (e.g., health, personal growth, spirituality, social relationships), and then you rated how important each domain was.

7. How has your relationship with pain changed since being in the group?
    - Clarification: By relationship, we mean the way you think about pain, or how you respond to pain.
    - Prompt: Is it different now from when you first completed the group a year ago?

Those are all the questions I have for you. Thank you so much for your participation in the study. We really appreciate it!

Appendix C

Interview guide for CBT group participants

We're asking questions to better understand your experience since the intervention and to get Veteran feedback on how to improve it for future Veterans. What will be most helpful is your honest feedback, so please feel free to be honest about your experience- you won't offend me!

As a reminder, you participated in a group called **Cognitive Behavioral Therapy for Chronic Pain.** You attended virtual group sessions with **[Therapist Name]** back in **[date of group]**.

In this group, you practiced relaxation strategies, liked guided imagery and progressive muscle relaxation. You also discussed pain-related thoughts and automatic negative thoughts, and activity pacing. Does this sound familiar?

I know that the study was a while ago, so it's okay if you don't remember all the details or if you are unsure how to answer some of the questions. There are no right or wrong answers. **What we're really interested in is if and how this group has helped you to be more engaged in your life such as in exercising, socializing, and household tasks**. We are also looking for how to improve the intervention. Do you have any questions before we get started?"

1. What was the most helpful part of the group for your pain? For example, are there any skills or aspects of the group you remember that have helped you manage your pain?
2. What from the group did you feel was less helpful for your pain or could use improvement?
    a. Prompt: What skills or aspects of the group do you remember that haven't helped you manage your pain?
3. When engaging in day-to-day activities now, how are you able to manage your pain?
4. What gets in the way of you managing your pain now?
5. What influence did the intervention have on your amount of activity including going on walks, getting out of the house, exercising, completing household chores, and spending time with friends or family?
    a. Prompt: Are you doing more of these activity since the intervention? Less?
    b. Prompt: Are you doing new or different kinds of activity?
    c. Prompt: Does your pain influence how much activity you do now?
        i. Prompt: How so?
6. I am now going to ask you about some specific topics covered in the group. Please tell me if and how you use each strategy to engage in more activities like getting out of the house, exercising, socializing, and completing household tasks when you have pain now?
    a. Do the relaxation strategies help you engage more in activities?
        i. Prompt: For example, you learned progressive muscle relaxation and guided imagery. For progressive muscle relaxation, you progressively relaxed the muscles of your body. For guided imagery, you imagined a relaxing scene.
    b. Does the idea of examining pain-related thoughts help you engage more in activities?

        i. Prompt: you discussed identifying and restructuring distorted thinking and automatic negative thoughts.
    c. Does activity pacing help you engage more in activities?
        i. Prompt: you discussed focusing on the amount of time you do an activity instead of the task itself.
7. How has your relationship with pain changed since being in the group?
    a. Clarification: By relationship, we mean the way you think about pain, or how you respond to pain.
    b. Prompt: Is it different now from when you first completed the group a year ago?

Those are all the questions I have for you. Thank you so much for your participation in the study. We really appreciate it!

Appendix D

Consolidated criteria for reporting qualitative studies (COREQ): 32-item checklist, reproduced from Tong et al. (2007).

Item	Guide Questions/Description
Domain 1: Research team and reflexivity	
Personal Characteristics	
1. Interviewer/facilitator	Which author/s conducted the interview or focus group?
2. Credentials	What were the researcher's credentials? E.g. PhD, MD
3. Occupation	What was their occupation at the time of the study?
4. Gender	Was the researcher male or female?
5. Experience and training	What experience or training did the researcher have?
Relationship with Participants	
6. Relationship established	Was a relationship established prior to study commencement?
7. Participant knowledge of the interviewer	What did the participants know about the researcher? e.g. personal goals, reasons for doing the research
8. Interviewer characteristics	What characteristics were reported about the interviewer/facilitator? e.g. Bias, assumptions, reasons and interests in the research topic
Domain 2: study design	
Theoretical framework	
9. Methodological orientation and Theory	What methodological orientation was stated to underpin the study? e.g. grounded theory, discourse analysis, ethnography, phenomenology, content analysis

Participant Selection

10. Sampling	How were participants selected? e.g. purposive, convenience, consecutive, snowball
11. Method of approach	How were participants approached? e.g. face-to-face, telephone, mail, email
12. Sample size	How many participants were in the study?
13. Non-participation	How many people refused to participate or dropped out? Reasons?

Setting

14. Setting of data collection	Where was the data collected? e.g. home, clinic, workplace
15. Presence of non-participants	Was anyone else present besides the participants and researchers?
16. Description of sample	What are the important characteristics of the sample? e.g. demographic data, date

Data Collection

17. Interview guide	Were questions, prompts, guides provided by the authors? Was it pilot tested?
18. Repeat interviews	Were repeat interviews carried out? If yes, how many?
19. Audio/visual recording	Did the research use audio or visual recording to collect the data?
20. Field notes	Were field notes made during and/or after the interview or focus group?
21. Duration	What was the duration of the interviews or focus group?
22. Data saturation	Was data saturation discussed?
23. Transcriptions returned	Were transcripts returned to participants for comment and/or correction?

Domain 3: analysis and findings

Data Analysis

24. Number of data coders	How many data coders coded the data?
25. Description of coding tree	Did authors provide a description of the coding tree?
26. Derivation of themes	Were themes identified in advance or derived from the data?
27. Software	What software, if applicable, was used to manage the data?
28. Participant checking	Did participants provide feedback on the findings?

Reporting

29. Quotations presented	Were participant quotations presented to illustrate the themes / findings? Was each quotation identified? e.g. participant number
30. Data and findings consistent	Was there consistency between the data presented and the findings?
31. Clarity of major themes	Were major themes clearly presented in the findings?
32. Clarity of minor themes	Is there a description of diverse cases or discussion of minor themes?

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