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Abstract

Borderline Personality Disorder (BPD) is characterized by a pattern of instability in self-image, interpersonal relationships, emotional regulation, and impulsivity that significantly impacts functioning in everyday life. Non-suicidal self-injury (NSSI) is a hallmark symptom of BPD that serves to regulate affective instability and relieve inner aversive tension. Experimental pain modalities are commonly employed to assess sensory perception in the context of BPD. Although the experience of self-inflicted pain during NSSI is thought to contribute to emotional regulation, individuals with BPD tend to exhibit reduced experimental pain sensitivity when compared to healthy controls. Thus, experimental pain reactivity may not adequately reflect mechanisms relevant to NSSI behaviors in BPD. Tactile sensory processing paradigms, which are believed to reflect cortical mechanisms underlying sensory perception, may be better suited to clarify the relationship between NSSI behaviors and sensory processing within BPD. The goal of the present study was to conduct the first pilot test of vibrotactile psychophysical measurement as a method of assessing tactile sensory processing among individuals with BPD symptoms that engage in NSSI. Primary outcomes included indices of feasibility/tolerability and tactile sensory processing. Fifteen participants were recruited for this pilot study ($n = 6$ in the BPD symptom condition, and $n = 9$ healthy controls). Results yielded evidence of feasibility (83.3% retention rate) and tolerability (no reported difficulties). Exploratory analyses further indicated that participants with BPD symptoms (vs. healthy controls) evinced faster choice than simple reaction time scores. No statistically significant differences were observed across the other paired sensory tasks. Collectively, these findings suggest that the vibrotactile psychophysical task paradigm is feasible, tolerable, and may have utility in the study of somatosensation among individuals with BPD symptoms.

A Pilot Study Examining Differences in Tactile Sensory Processing as a
Function of Borderline Personality Disorder Symptomatology and Non-Suicidal Self-Injury

by

Julia E. Hooker

B.A., Connecticut College, 2015

Thesis

Submitted in partial fulfillment of the requirements for the degree of

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A Pilot Study Examining Differences in Tactile Sensory Processing as a
Function of Borderline Personality Disorder Symptomatology and Non-Suicidal Self-Injury

Borderline Personality Disorder (BPD) is characterized by a pattern of instability in self-image, interpersonal relationships, emotional regulation, and impulsivity that negatively impacts daily functioning (American Psychiatric Association, 2013). Individuals with BPD experience severe psychosocial impairments, and often engage in impulsive and self-destructive behaviors (Lieb, Zanarini, Schmahl, Linehan, & Bohus, 2004). Additionally, disturbed affective responding and affective dysregulation are core symptoms of BPD (Niedtfeld et al., 2012). Individuals with BPD (vs. without BPD) tend to experience more frequent mood swings and pronounced negative emotions in everyday life, often cycling through states of dysphoria and euthymia during the course of a single day (Lieb et al., 2004). BPD is also associated with a high mortality rate due to suicide, with up to 10% of individuals diagnosed with BPD eventually dying by suicide (Lieb et al., 2004).

Symptoms of BPD typically emerge during early adulthood, and estimated prevalence rates in the general population range from approximately 1.5-6% (American Psychiatric Association, 2013; Grant et al., 2008; Torgersen, 2009). Within treatment settings, the prevalence of BPD may be as high as 10% among psychiatric outpatients and 20% among psychiatric inpatients (Lieb et al., 2004). Though BPD is often assumed to be a lifelong diagnosis, longitudinal studies indicate that it often remits after a period of 2-6 years (Torgersen, 2009; Zanarini, Frankenburg, Hennen, Reich, & Silk, 2006; Zanarini, Frankenburg, Hennen, & Silk, 2003). For example, a 10-year longitudinal investigation of the course of BPD in 290 inpatients found that after 10 years, 88% of the patients with BPD had achieved remission (Zanarini et al., 2006).

Individuals with BPD tend to utilize substantial mental health treatment resources over the course of their illness, including both psychosocial and psychopharmacologic intervention modalities (Bender et al., 2001; Lieb et al., 2004). Indeed, it has been estimated that 72% of individuals with BPD will undergo psychiatric hospitalization at some point in their lifetime (Lieb et al., 2004). Individuals with BPD also tend to utilize more general health resources, relative to the general population (Dixon-Gordon, Conkey, & Whalen, 2017). For example, several studies that examined data from the National Epidemiologic Survey of Alcohol and Related Conditions (NESARC) observed positive associations between incidence of BPD and gastrointestinal, cardiovascular, hepatic, chronic pain, or “any” other disease/disorder (Dixon-Gordon et al., 2017; El-Gabalawy, Katz, & Sareen, 2010).

BPD has also been linked to significant public and mental health costs. For example, the economic impact of BPD (largely as function of healthcare and lost productivity) has been estimated to be larger than that of Major Depressive Disorder and other personality disorders (Bender et al., 2001). The presence of non-suicidal self-injury (NSSI; defined as “direct and deliberate bodily harm in the absence of suicidal intent”) among individuals with BPD further escalates these costs, as hospitalization is common in the context of NSSI (Bender et al., 2001; Gunnell, Brooks, & Peters, 1996; Rissmiller, Steer, Ranieri, Rissmiller, & Hogate, 1994; Rodger & Scott, 1995). Given prevalence of the disorder, significant health comorbidities, and associated costs, mechanisms underlying NSSI behaviors among individuals with BPD should be a significant focus of BPD research.

The Function of NSSI in Borderline Personality Disorder

An estimated 69%-90% of patients diagnosed with BPD engage in NSSI (Zanarini et al., 2006), and the presence of self-injurious behavior is a criterion for the diagnosis of BPD

(American Psychiatric Association, 2013). The most commonly reported type of NSSI is cutting or carving the skin with a sharp object, such as a knife or a razor (Nock, 2010; Nock & Prinstein, 2004). The majority of individuals who self-injure endorse using multiple methods, including scratching or scraping the skin, inserting objects under the skin, and burning the skin (Nock, 2010). Less commonly reported methods include hitting/biting oneself and picking at old wounds (Nock, 2010). NSSI in the context of BPD is usually repetitive, unlikely to cause serious physical or fatal harm, but is a risk factor for both future suicide attempts and completed suicide (Herpertz, 1995; Kleindienst et al., 2008). NSSI is often described as serving to relieve aversive inner tension (Brown, Comtois, & Linehan, 2002; Schmahl & Baumgartner, 2015). Research has consistently documented associations between self-injurious behavior and BPD diagnosis (Klonsky, 2007), and contemporary conceptual models posit that NSSI is often employed to regulate emotional experiences (Koenig, Thayer, & Kaess, 2016; Nock & Prinstein, 2004; Reitz et al., 2015; Schmahl & Baumgartner, 2015).

Altered Sensory Processing in Borderline Personality Disorder

Altered sensory processing has been an area of increasing interest in the BPD literature, particularly as it relates to NSSI behaviors and emotion regulation. The role of the somatosensory sub-modality of pain has largely been the focus of investigations of sensory processing in BPD, and explorations of sensory perception outside of the pain experience remain limited (Schmahl & Baumgartner, 2015). A converging body of evidence demonstrates reduced pain sensitivity among individuals with BPD. For example, an early study of self-injurious behaviors found that more than 50% of individuals with BPD reported no pain during episodes of self-injury (Leibenluft, Gardner, & Cowdry, 1987). Laboratory investigations examining pain perception as a function of BPD have evinced similar results. For example, pain ratings during a

cold pressor task were significantly lower (i.e. rated as less painful) among subjects with BPD who reported not experiencing pain during self-injury (vs. healthy controls and subjects with BPD who reported experiencing pain during self-injury; Russ, Campbell, Kakuma, Harrison, & Zanine, 1999; Russ et al., 1992).

Individuals with BPD also tend to evince higher experimental pain thresholds (i.e. the point at which a stimulus is first identified as painful) when compared to healthy controls (Bohus et al., 2000; Schmahl et al., 2006). Bohus et al. (2000) investigated the effect of subjective distress (or aversive tension) on pain perception in individuals with BPD that reported analgesia during NSSI. Individuals with BPD exhibited higher pain thresholds than did healthy controls when experiencing low levels of stress (Bohus et al., 2000). Interestingly, this difference in pain perception was further enhanced when the BPD group participants were experiencing subjectively high levels of distress. In other words, participants with BPD were less sensitive to pain than healthy controls, and this finding was amplified in the presence of high distress. These findings corroborate earlier evidence of reduced pain perception in individuals with BPD, and suggests there may be some underlying sensory mechanism unique to individuals with BPD that influences their propensity to engage in NSSI. This study also accounted for the influence of stress-induced analgesia (i.e. an automatic pain-suppression response following exposure to a stressful stimulus) and ruled it out as an artifact that could have influenced the self-reported pain experience of individuals with BPD.

Cortical Mechanisms Underlying Sensory Processing in Borderline Personality Disorder

Though self-report measures of somatosensation and laboratory examinations of pain-related sensory stimuli have highlighted broad differences in sensory processing between individuals with BPD and healthy controls, recent research has employed brain imaging (e.g.,

functional magnetic resonance imaging; fMRI) to study cortical mechanisms underlying affect regulation and somatosensation in BPD populations. For example, fMRI investigations of sensory alterations in BPD have found that sensory stimulation decreases activity in brain areas associated with emotional arousal independent of pain experience (Niedtfeld et al., 2010; Niedtfeld et al., 2012). Introducing heat stimulation after inducing negative affect in individuals with BPD revealed decreased amygdala and anterior cingulate cortex activation independent of perceived pain intensity. These results support previous findings of emotional hyperactivity in BPD (Ebner-Priemer et al., 2007), and suggest that not just painful, but perhaps also general sensory stimuli are processed differently in BPD. This study was the first to investigate connections between affective regulation and sensory stimuli similar to pain in BPD, and suggests that modalities beyond those specific to pain may help to clarify the relationship between sensory stimuli involved in NSSI and affective regulation.

There is evidence to suggest that brain networks linked to attentional focus and the appraisal of sensory stimuli may influence negative affect regulation in the context of NSSI. For example, Niedtfeld et al. (2012) observed enhanced connectivity between the dorsolateral prefrontal cortex (dlPFC), which is associated with appraisal of stimuli, and the medial frontal gyrus, which is associated with attentional shift, in individuals with BPD following heat stimulation (Niedtfeld et al., 2012). Kluetsch et al. (2012) further observed significant alterations in the default mode network (DMN) as a function of BPD status, indicating that subjects with BPD appraised pain as less self-relevant and less aversive than did healthy controls. The DMN may be implicated in self-referential pain and pain processing, and was hypothesized within this study to be connected to limbic and prefrontal brain regions, such as the anterior cingulate cortex and amygdala. Taken together with previous findings that sensory stimulation decreases activity

in brain areas associated with emotional arousal independent of pain experience, these data suggest that additional exploration of general sensory perception may help to disentangle the relationship between pain-specific and general sensory-related cortical mechanisms.

Unfortunately, previous studies of pain-related neural mechanisms have generally excluded measures of general sensory processing, and studies of sensory perception among individuals with BPD have typically not examined the role of attentional processes. Utilizing measures of sensory processing that probe cortical pathways underlying somatosensation and attentional processes that impact sensory perception may clarify the ways in which they interrelate.

General Sensory Perception and Borderline Personality Disorder

Despite a large body of evidence supporting attenuated pain perception in BPD, the presence and nature of other somatosensory deficits within BPD remain unclear. In a study conducted by Schmahl and colleagues (2004), laser-evoked potentials (LEPs) were used to differentiate factors underlying pain analgesia during NSSI among individuals with BPD. LEPs are a method of quantitative sensory testing used to document reduced sensory sensitivity that results from the use of laser heat. Participants with BPD were found to have significantly higher radiant heat detection thresholds than healthy controls. Within this portion of the study, the heat sensations being detected did not include stimuli that would cause pain, and therefore participants responded simply to the presence of non-painful temperature stimuli. In other words, BPD participants experienced diminished sensory perception in the context of heat sensations that were not painful (Schmahl et al., 2004). Interestingly, it appeared that analgesia experienced in BPD was not due to a generalized impairment of the sensory-discriminative pain component, or to any attention deficits in individuals with BPD (Schmahl et al., 2004). This finding suggests that altered sensory processing in BPD may be due to a more specific impairment in sensory

processing that was not captured by the generalized sensory impairment measure. Indeed, these measures may not have yielded enough granular sensory information to identify specific sensory deficits. Utilizing more sensitive tools to assess sensory impairment may further clarify which aspects of sensory perception may differ as a function of BPD.

Exteroception and Proprioception in Borderline Personality Disorder

Expanding upon the hypothesis that a generalized dysfunction in somatosensory systems exists in individuals with BPD, Pavony & Lenzenweger (2014) conducted a study including measures of exteroception (basic touch) and proprioception (body sense) somatosensory sub-modalities (Pavony & Lenzenweger, 2014). Though participants with BPD (vs. without BPD) demonstrated lower (i.e. worse) discriminability between stimuli of different weights being applied to their fingertips, proprioceptive deficits in the BPD group were related to higher BMI (Pavony & Lenzenweger, 2014). Body mass index has previously been related to exteroceptive deficits when somatosensation is measured using the two-point discrimination task (TPDT; the task used within the study to measure exteroception), which could in part explain the lack of observed differences in exteroceptive abilities (Falling & Mani, 2016). Tasks measuring more specific somatosensation abilities may better capture exteroception as it relates to NSSI behaviors. Notably, participants in this study were not separated by presence or absence of NSSI behaviors within BPD. The current lack of significant somatosensory findings may be attributable to grouping participants with BPD who do and do not engage NSSI behaviors.

The Influence of NSSI on Sensory Processing

NSSI behaviors themselves may account for somatosensory processing deficits in individuals with BPD. In a study of NSSI and sensory perception outside of the context of BPD, Hooley and colleagues (2010) found that frequency of NSSI behaviors was related to diminished

sensory detection abilities (Hooley, Ho, Slater, & Lockshin, 2010). This indicates that the NSSI component of BPD may help to differentiate individuals with BPD who have altered sensory perception from those who do not. Tactile sensory processing in BPD has not yet been investigated in the context of NSSI, which is unfortunate because examination of mechanisms underlying altered sensory perception in BPD could help to elucidate relations between general sensory perception and self-injurious behaviors. Previous investigations of NSSI and somatosensation in BPD have employed tools that only capture broad information about sensory processing capabilities, and do not necessarily reflect cortical mechanisms underlying somatosensation. Advances in the measurement of tactile sensory processing may provide more specific information regarding sensory perception among individuals with BPD.

Tactile Sensory Processing

Tactile sensory processing reflects the ability to detect and interpret sensory signals relating to touch, vibration, pressure, temperature, and pain (Abraira & Ginty, 2013). Although the tactile sensory sub-modality of pain discussed earlier is included under the broad heading of tactile sensory processing, other types of somatosensation (primarily pressure and vibration discrimination abilities) are also linked to cortical functioning (Puts et al., 2013). Cortical functioning in areas related to somatosensation has been linked to measurable aspects of behavior, such as difficulties with sensory encoding and decision making (Puts et al., 2011). Puts and colleagues (2011) further observed that ability to discriminate between frequencies of vibration applied to the fingertips was directly correlated with GABA concentration in the sensorimotor cortex. Although GABA concentration has previously been shown to differ between individuals with BPD and healthy controls (and has been associated with symptoms of impulsivity in BPD; Ende et al., 2016), prior investigations of sensory processing among

individuals with BPD have not included tasks that relate to GABA concentration. We contend that exploring tactile sensory processing using vibration stimuli that reflect GABA concentration has the potential to uncover differences between individuals with BPD symptoms and healthy controls that have not been identifiable with previously employed methods. Indeed, whereas tasks assessing pain processing have been linked primarily to larger brain networks, tactile sensory processing tasks (e.g. detection threshold and amplitude discrimination tasks) are thought to reflect neurotransmitter concentrations within the sensorimotor cortex (Kluetsch et al., 2012; Niedfeldt et al., 2012), and thus may be better suited to explicate neural mechanisms that are more specific to sensory perception.

Previous studies using the same vibrotactile psychophysical measurement have found that children with Autism Spectrum Disorder (ASD) exhibit poorer discrimination between different vibration stimuli delivered simultaneously than do typically-developing children (TDC; Puts et al., 2014). Additionally, differences in performance between paired vibrotactile psychophysical tasks suggests that a functional deficit in the somatosensory inhibitory system may exist in ASD but not in TDC (Puts et al., 2014). Similar results have been obtained in populations with Obsessive-Compulsive Disorder (OCD), which also suggest that alterations in cortical functioning impact somatosensory processing abilities (Guclu et al., 2015). Vibrotactile psychophysical task performance can reflect changes in cognitive plasticity, alterations in cortical functioning, and neural correlates of sensory encoding (Tommerdahl, Dennis, Francisco, Holden, Nguyen, & Favorov, 2016; Puts et al., 2011).

The Current Study

Though it has been demonstrated that altered pain-related sensory processing exists in BPD (e.g. Bohus et al, 2000; Niedfeldt et al., 2010; Reitz et al., 2015), the presence of altered

tactile sensory processing in BPD remains unexplored. Additionally, although altered sensory processing and NSSI behaviors may be related in BPD, the mechanism through which sensory processing may influence NSSI behaviors has not yet been studied. The goal of the present study was to conduct a pilot investigation of somatosensory processing in the context of NSSI behaviors and BPD symptoms using a novel vibrotactile psychophysical paradigm.

Prior investigations of non-pain-related sensory processing in BPD have only used detection thresholds of laser-evoked heat stimuli, weight discrimination, or basic touch using a two-point discrimination task (Schmahl et al., 2004; Pavony & Lenzenweger, 2014). No previous research has examined associations between BPD and tactile sensory processing across a variety of experimental sensory processing tasks (i.e., detection threshold; amplitude/duration discrimination; reaction time; and temporal order judgment). Although each of these outcomes was assessed in the current study, exploratory hypotheses focused on detection threshold and amplitude discrimination, as these tasks have been most consistently been invoked to differentiate tactile sensory processing abilities between populations that tend to experience sensory alterations and healthy controls (Puts, Wodka, Tommerdahl, Mostofsky, & Edden, 2014; Puts et al, 2017).

Detection threshold. Detection threshold tasks are typically used to evaluate general tactile sensory sensitivity by measuring ability to identify a static vibrating stimulus, and by examining performance differences on two detection tasks that probe sensory filtering and feed-forward inhibition (Puts et al., 2014). Previous research has shown that individuals with ASD exhibit reduced sensitivity as measured by static detection threshold, as well as impaired feed-forward inhibition on this task (Puts et al., 2014). Detection threshold measures the amount of stimulation needed to detect a vibration, and mirrors heat detection tasks that have previously

been used to explore sensory perception in individuals with BPD (Schmahl et al., 2004).

Utilizing a similar task without the interference of temperature or pain sensations might clarify whether individuals with BPD experience reduced sensitivity to sensory stimuli in the absence of pain. Similarities between the detection threshold task and previous measurements of sensory perception in individuals with BPD (e.g., heat detection) make it a natural area of exploration using this novel vibrotactile psychophysical paradigm. Thus, we hypothesized that participants in the BPD symptom group would exhibit reduced sensory sensitivity via higher static and dynamic detection thresholds, when compared to healthy controls.

Amplitude discrimination. Amplitude discrimination tasks are typically used to evaluate sensory inhibition and sensory filtering by comparing the ability to determine which of two simultaneously applied vibration stimuli is stronger when another stimulus that has been shown to impair this ability in healthy controls is introduced. Examining ability to filter out irrelevant sensory stimuli (known as an adaptation) has previously been used to differentiate populations that experience sensory alterations (such as in Autism Spectrum Disorder and ADHD) from healthy controls (Puts et al., 2014; Puts et al, 2017). For example, although individuals with Autism Spectrum Disorder (ASD) have been shown to exhibit deficits in amplitude discrimination, the presence of an adapting stimulus (or using a pre-trial vibration to create a physical contrast between the adaptation and the actual stimulation) appeared to have little effect on their ability to discriminate between vibrations (whereas presence of the same adapting stimulus worsened performance among healthy controls; Puts et al., 2014). Collectively, these findings suggest a potential functional deficit in the somatosensory inhibitory system in ASD, as well as difficulties related to sensory filtering (Puts et al, 2014). Examining performance on the amplitude discrimination task among individuals with BPD symptoms may also provide

evidence that previous findings of overlapping symptoms in BPD and ASD (Chabrol & Raynal, 2018; Dudas et al., 2018; Ryden, Ryden, & Hetta, 2008) extend to sensory perception capabilities (Puts et al., 2014). Utilizing the same methods of measurement among individuals with BPD may help to clarify the nature of existing tactile sensory deficits within this population. Thus, we hypothesized that individuals within the BPD symptom group will exhibit sensory deficits as measured by the amplitude discrimination task (i.e. diminished ability to discriminate between stimuli of different amplitudes, and no influence of an adapting stimulus) as compared to healthy controls.

Other sensory processing tasks. Reaction time, duration discrimination, and temporal order judgment tasks are intended to assess attention and reaction speed to sensory stimuli, the ability to discriminate between the length of two vibration stimuli, and the ability to identify the order in which sensory stimuli are delivered, respectively. Previous research has shown that mean reaction times measured using vibrotactile paradigms have not differed significantly between populations that experience sensory alterations and healthy controls (Puts et al., 2014). As reaction time tasks can probe attentional abilities, this task is still of interest within the present study given previous findings relating to attention within BPD populations, and may provide novel insight into somatosensory processing in individuals with BPD symptoms (Puts et al., 2013; Niedtfeld et al., 2012). Findings relating to temporal order judgment and duration discrimination have been mixed within populations that experience sensory alterations, with some studies indicating differences between clinical populations and healthy controls and others indicating no differences (Puts et al., 2014; Tommerdahl, Tannan, Holden & Baranek, 2008; Tommerdahl et al., 2016). Nonetheless, information gleaned from reaction time, duration discrimination, and temporal order judgment tasks could help to clarify past inconsistencies

within the sensory processing literature, and future research may benefit from evidence that these tasks can be successfully implemented among individuals with BPD symptoms who engage in NSSI behaviors.

The current study is the first to examine tactile somatosensory deficits among individuals with BPD symptoms who report having engaged in NSSI. As such, the primary aims were to (1) assess feasibility and tolerability of the study protocol, and (2) explore tactile sensory processing outcomes (i.e., detection threshold; amplitude/duration discrimination; reaction time; and temporal order judgment) as a function of study group (i.e. BPD symptom group vs. healthy controls).

Hypotheses

Hypothesis 1. The study procedure will be feasible and tolerable. Feasibility and tolerability will be assessed by examining recruitment/retention rates and participant reports.

Exploratory Hypothesis 2. BPD symptom group participants (vs. healthy controls) will exhibit deficits in tactile sensory processing abilities measured by the detection threshold and amplitude discrimination tasks. More specifically, participants with BPD symptoms will exhibit higher detection thresholds and no influence of an adapting stimulus on the amplitude discrimination task.

Method

Participants

Participants were recruited from the Syracuse, New York area for a larger parent study investigating neural markers for suicidality in BPD (see Figure 1). Thus, the inclusion and exclusion criteria for the present study match that of the parent study. All participants were between 18 and 45 years of age and right-handed, and individuals taking prescription

medications other than SSRIs or SNRIs were excluded. Primarily due to ethical and practical considerations (e.g., wash-out periods), previous studies using the CM5 vibrotactile psychophysical paradigm have not required that participants discontinue their use of medication prior to participation (Guclu et al., 2015; Puts et al., 2016). Participants completed a telephone screening to determine eligibility prior to the study.

BPD Symptom Condition. To be included in the BPD symptom condition, participants were required to meet criteria for 3 or more symptoms of BPD as measured by the Structured Clinical Interview for DSM-5 Personality Disorders (SCID-5-PD; First, Williams, Benjamin, & Spitzer, 2015) and report having engaged in NSSI at least five times within the past year. Participants were also excluded if they met criteria for any current or former moderate or severe substance use disorder as measured by the Structured Clinical Interview for DSM-5, Research Version (SCID-5-RV; First, Williams, Karg, & Spitzer, 2015). Participants with any significant current medical conditions (such as epilepsy) were also excluded. Participants in the BPD symptom group with any history of suicide attempt were required to be seeing a mental health care provider to be eligible for the parent study.

Healthy Control Condition. Healthy control participants could not meet criteria for more than 1 symptom of BPD, and must not have met criteria for any current psychiatric disorders. They were required not to have met current or former criteria for any moderate or severe substance use and must not have had any current opiate use (including prescription opioids) or past history of opiate abuse. Healthy control participants were also excluded if they reported a history of self-injurious behaviors or suicidality, or the presence of significant current medical conditions (such as epilepsy).

Procedure

Recruitment flyers were placed in the local community. Potential participants were screened via phone to determine eligibility. First, participants were asked questions pertaining to demographics, height, and weight. Participants were then asked if they had engaged in NSSI behaviors in the past year. Potential participants who endorsed past-year NSSI were queried to determine the frequency of this behavior. Participants were further screened using the SCID-5-RV substance use module and the SCID-5-PD BPD module.

Laboratory Session 1. Eligible participants were invited to participate in the larger parent study, and scheduled for an initial in-person laboratory visit during which they all underwent the procedures outlined in Figure 2. After providing informed consent, participants were screened for alcohol and drug use using a urine toxicology test and alcohol breathalyzer test. Graduate research assistants conducted interviews with participants to assess demographic information, BMI, past NSSI and suicide-related behaviors, personality characteristics, and DSM-5 diagnoses as classified by the SCID-5. Participants then completed a testing battery to assess somatosensory processing abilities. This was assessed using the CM5 two-digit vibrotactile stimulator (Cortical Metrics). All stimuli were delivered to the glabrous skin of the left hand on digit 2 (LD2) and digit 3 (LD3) using a cylindrical probe that is 5mm in diameter. Participants followed instructions presented to them on a laptop connected to the stimulator. The online program (Brain Gauge) displayed practice trials with initial task instructions to ensure that each participant understood the task. Graduate research assistants remained in the room to monitor task progress. As described in the measures section below, the battery consisted of 5 tasks assessing different aspects of tactile sensation perception, with each task having two separate conditions (Puts et al., 2014). This laboratory session lasted about three hours, including

30 minutes for the sensory testing battery. The data for the present study were collected solely from this initial study visit.

Laboratory Session 2 and fMRI Session. The parent study included a second psychophysiological testing session and an fMRI study session. The second in-person laboratory session included sensory testing via pain stimulation, the Wechsler Abbreviated Scale of Intelligence, 2nd edition (Wechsler, 2011), measures of chronic stress and current life stressors, and an fMRI eligibility screening. The order of laboratory visits was selected to decrease the chance of pain stimulation in session 2 interfering with the vibrotactile sensory testing in session 1. The fMRI study visit lasted two hours and assessed resting state activity as well as reactivity to stressful visual stimuli. Participants were compensated \$70 for their participation in laboratory session 1, and \$100 for their participation in laboratory session 2.

Measures

Sociodemographic Characteristics

Sociodemographic characteristics, including age, gender, race, ethnicity, and education, were obtained via self-report.

Vibrotactile Psychophysical Tasks

Somatosensory capabilities were assessed using a CM5 two-digit vibrotactile stimulator (Cortical Metrics, LLC; model CM5). The vibrotactile sensory testing battery consisted of five tasks, each with two conditions; prior to each task, participants had to correctly respond to three practice trials to ensure that they correctly understood the instructions before proceeding. On-screen feedback was given to participants during the practice trial, but not during the task trials themselves. Before beginning the testing battery, participants placed their left hand on the stimulator, with digits 2 and 3 on separate cylindrical probes. Participants indicated their

responses via mouse-click using their right hand. Each of the five sensory tasks and their conditions are described in further detail below. Sensory processing abilities were measured on a task-specific level across the 5 somatosensory tasks. These tasks are commonly used to measure sensory processing across a variety of populations (Nelson et al., 2012; Puts et al., 2013; 2-14; 2017; Tavassoli et al., 2017).

Detection Threshold. The detection threshold task consisted of two conditions: Static detection threshold and dynamic detection threshold. For the static detection threshold condition, participants were asked to determine on which finger they felt a weak static stimulus. The amplitude of the vibration would decrease after a correct identification of the stimulus site and increase after an incorrect identification. Static detection threshold was calculated as the mean amplitude of the final four trials. The dynamic detection threshold condition asked that participants identify on which finger they felt a vibration. The amplitude of the vibration began at zero and increased until the participant was able to detect it. Dynamic detection threshold was measured as the mean stimulus amplitude at the time of the mouse-click across all correct trials. The detection threshold task was measured as amplitude of the vibration in milliseconds (ms).

Amplitude Discrimination. The amplitude discrimination task consisted of two conditions: Amplitude discrimination with no adaptation and amplitude discrimination with a single-site adaptation. In the no-adaptation condition, participants were asked to choose which of two simultaneously delivered stimuli had the higher amplitude. Comparison stimulus amplitude was decreased for a correct answer and increased for an incorrect answer. In the single-site adaptation condition, each trial was preceded by single-site delivered adapting stimulus of 1 second. Amplitude discrimination thresholds were calculated as the mean amplitude of the final

four trials. The amplitude discrimination task was measured as amplitude of the vibration in micrometers (μm).

Reaction Time. The reaction time task consisted of two conditions: Simple reaction time and choice reaction time. Participants were asked to respond as quickly as possible when they felt a vibrating stimulus (frequency 25 Hz, amplitude 300 μm , duration 40 ms). The simple reaction time condition asked that participants click the mouse when they felt a vibration. The choice reaction time condition asked that participants determine which finger received the stimulus (left or right). Each trial of each condition had an intertrial interval of 3 seconds, and each condition included 20 trials. Mean reaction time was calculated by sorting reaction times in order (only including the correct trials for the choice reaction time condition), and averaging the median six values. The reaction time task was measured in milliseconds.

Duration Discrimination. The duration discrimination task consisted of two conditions: Simple duration discrimination and duration discrimination with a confound. In the simple duration discrimination condition, participants were asked to identify which of two sequentially delivered vibrations (to each finger separately) was of longer duration. Duration of the test stimulus was decreased when subject responses were correct, and increased when responses were incorrect. In the duration discrimination with a confound condition, participants completed the same duration discrimination task, but received the stimuli with an increased standard amplitude to make it more difficult to discriminate the duration of the stimulus. Duration discrimination was measured as amplitude of the vibration in micrometers (μm).

Temporal Order Judgment. The temporal order judgment task consisted of two conditions: Simple temporal order judgment and temporal order judgment with a carrier. In the simple temporal order judgment condition, participants were asked to determine which finger

received the first of two sequentially, but temporally separated, stimuli. In the temporal order judgment with a carrier condition, participants completed the same task, but with a 25hz concurrent carrier stimulus that was delivered throughout each 1 second trial interval. The temporal order judgment task was measured as time in milliseconds.

Body Mass Index

Height and weight measurements were taken to calculate a Body Mass Index (BMI) value for each participant. BMI has been found to influence measures of proprioception in previous studies examining BPD and sensory perception (Pavony & Lenzenweger, 2014).

Non-Suicidal Self-Injurious Behaviors

The Self-Injurious Thoughts and Behaviors Interview – Short Form (SITBI) is a structured clinical interview that assesses the presence, frequency, and characteristics of a wide range of self-injurious thoughts and behaviors including NSSI, suicidal ideation, suicide plans, and suicide attempts (Nock, Holmberg, Photos, & Michel, 2007). This measure includes 72 items in six modules that assess six different types of suicide-related and self-injurious thoughts and behaviors as well as the frequency and intensity of those thoughts and behaviors. Those modules include suicidal ideation, suicide plan, suicide gesture, suicide attempt, thoughts of NSSI, and NSSI. The SITBI has strong interrater reliability ($k = .99$, $r = 1.0$) and concurrent validity with other measures of NSSI ($k = .87$; Nock, Holmberg, Photos, & Michel, 2007). Past-year frequency of NSSI was measured as a count of instances of NSSI within the past year.

Data Analytic Plan

All analyses were conducted using SPSS Statistics 25 (IBM SPSS Statistics, 2017). Descriptive statistics were calculated for baseline demographics, BPD symptoms, NSSI frequency, and each of the psychophysical task outcomes. Consistent with established guidelines,

feasibility was assessed by examining recruitment rates, consent rates, completion rates, and qualitative tolerability feedback (Bell, Whitehead, & Julious, 2018; Thabane et al., 2010). Psychophysical task outcomes for each of the participant groups were calculated as 95% confidence intervals (CI).

Consistent with standard practices for interpreting pilot study data, the following portion of the data analytic plan should be viewed as exploratory in nature, with potential to inform future research (Lee, Whitehead, Jacques, & Julious, 2014). First, a series of Kendall's tau-b bivariate and point-serial correlations were run to explore associations between sociodemographic factors, BMI, NSSI frequency, and scores on each of the 10 vibrotactile psychophysical task conditions. Variables that were associated with dependent variables were retained as covariates in subsequent analyses.

Second, distributions of all outcome variables (psychophysical task condition scores) were then examined for normality. Consistent with standard procedures, cutoff values of ± 2.00 for measures of skewness and kurtosis were used to indicate a normal distribution (George & Mallery, 2010). Skewness and kurtosis values fell within acceptable ranges for reaction time, amplitude discrimination, and detection threshold (see Table 1). However, logarithmic transformations (McDonald, 2014) were applied to address skewness and kurtosis values for temporal order judgment (temporal order judgment, simple: skewness =.552, kurtosis =.208; temporal order judgment, carrier: skewness =.285, kurtosis =-.400) and duration discrimination (duration discrimination, simple: skewness =.324, kurtosis = -.105; duration discrimination, confound: skewness =.223, kurtosis =.354).

Lastly, consistent with prior studies using the Cortical Metrics device (Nelson et al., 2012; Puts et al., 2017), one-way repeated measures analysis of covariance procedures

(ANCOVAs) were conducted for each of the five psychophysical tasks. Condition was the dependent measure (for example, static and dynamic detection threshold). The main effects of sensory task condition and subject group (BPD symptom participants or healthy controls) as well as interactions are reported for each task. For all ANCOVA models, the magnitude of group differences was examined using partial eta squared (η_p^2), with values of 0.01, 0.09, and 0.25 characterizing effects as small, medium, or large (Cohen, 1973). Paired t-tests were used to compare performance on the five paired task conditions (e.g. between simple and choice reaction time tasks).

Results

Participant Characteristics

The current sample was comprised of 15 participants, including $n = 9$ in the healthy control group (33.3% Male; $M_{age} = 21.96$, $SD = 2.85$), and $n = 6$ in the BPD symptom group (66.7% male; $M_{age} = 25.60$, $SD = 3.70$). As expected, the mean BPD symptom count was 0.44 ($SD=0.73$) among healthy control participants and 4.83 ($SD = 2.04$) among BPD symptom group participants ($p < .01$). Among BPD symptom group participants, the mean number of instances of past-year NSSI was 31.2 ($SD = 19.65$). Three of the six BPD symptom group participants met full criteria for BPD. The sample was predominantly white (60%) and well-educated (all participants had completed some college). Sociodemographic and clinical data are presented in Table 2.

Feasibility Outcomes

Recruitment and Retention. Potential participants ($n = 79$) recruited from the Syracuse, NY community were screened for eligibility. The recruitment rate for the present sample was 22.8%; of the original 79 screened participants, $n = 18$ met eligibility criteria for the study and

were subsequently consented. Of the consented participants, 11.1% ($n = 2$) were deemed ineligible at the laboratory experimental session due to substance use or lack of a mental healthcare provider, and 5.6% ($n = 1$) did not return to complete the vibrotactile sensory testing battery. Of the 18 consented participants, $n = 15$ completed the study, indicating an 83.3% rate of retention.

Tolerability of the Sensory Battery. 100% of the participants who completed sensory testing ($n = 15$) tolerated the testing battery. The single consented participant ($n = 1$) who did not complete the sensory testing battery left their session early for reasons unrelated to the testing battery; this participant declined to return for a follow-up visit. None of the participants who completed the sensory testing battery reported any complaints or discomfort. Additionally, no participants reported difficulty understanding the on-screen instructions. Total testing time per participant was approximately 30 minutes.

Correlations

Bivariate and point-serial Kendall's tau-b correlations between psychophysical tasks, sociodemographic factors, BMI, NSSI frequency, and BPD symptoms for the entire sample are presented in Table 3. As expected, BPD symptom count was positively correlated with past-year NSSI frequency ($\tau_b = .710, p = .002$). A positive correlation was also observed between race and static detection threshold ($\tau_b = .478, p = .034$), and between race and temporal order judgement with a carrier ($\tau_b = .520, p = .021$). Separate t-tests were then used to examine differences in task performance by race. Specifically, Non-White participants had higher static detection ($M = 10.00, SD = 2.56$) and temporal order judgment with carrier thresholds ($M = 70.92, SD = 43.45$) than did White participants ($M = 7.11, SD = .625, p < .05; M = 32.62, SD = 19.38, p < .05$). Further positive correlations were observed between age and simultaneous amplitude

discrimination ($\tau_b=.413$, $p = .033$), as well as education and simultaneous amplitude discrimination ($\tau_b=.446$, $p = .050$). Thus, race, education, and age, were included as covariates in subsequent analyses. No additional covariates were identified via bivariate analyses.

Psychophysical Task Outcomes

Detection Threshold. Mean static and dynamic detection threshold were 8.04 ± 2.14 (95% CI [3.11, 12.97]) and $8.34 \pm 3.75 \mu\text{m}$ (95% CI [-0.31, 16.99]), respectively, for healthy controls. Mean static and dynamic detection threshold were 8.60 ± 2.37 (95% CI [2.51, 14.69]) and $8.70 \pm 3.52 \mu\text{m}$ (95% CI [-0.35, 17.75]), respectively, for participants with BPD symptoms (Figure 3b). Exploratory repeated measures ANCOVAs revealed no effect of group, $F(1,13)=.155$, $p = .700$, $\eta_p^2 = .012$, or task $F(1,13)=.033$, $p = .859$, $\eta_p^2 = .003$, and no interaction $F(1,13)=.008$, $p = .929$, $\eta_p^2 = .001$. In both healthy controls and participants with BPD symptoms, paired t-tests revealed no differences between dynamic and static detection thresholds (healthy controls: $t(8)=-.178$, $p = .863$; BPD symptoms participants: $t(6)=-.111$, $p = .916$).

Amplitude Discrimination. Mean no-adaptation and single-site adaptation amplitude discrimination thresholds were $24.40 \pm 8.13 \mu\text{m}$ (no-adaptation; 95% CI [5.65, 43.15]) and $72.95 \pm 24.32 \mu\text{m}$ (single-site adaptation; 95% CI [16.87, 129.03]) for healthy controls. Mean no-adaptation and single-site adaptation amplitude discrimination thresholds were $29.97 \pm 12.23 \mu\text{m}$ (no-adaptation; 95% CI [-1.47, 61.41]) and $58.78 \pm 23.99 \mu\text{m}$ (single-site adaptation; 95% CI [-2.90, 120.46]) for participants with BPD symptoms (Figure 3c). Exploratory repeated measures ANCOVAs revealed no effect of group, $F(1,11)=.942$, $p = .353$, $\eta_p^2 = .079$, or task $F(1,11)=.447$, $p = .518$, $\eta_p^2 = .039$, and no interaction $F(1,11)=.594$, $p = .457$, $\eta_p^2 = .051$. Paired t-tests revealed a significant difference between no-adaptation and single-site adaptation amplitude discrimination

thresholds among the healthy control group, $t(8)=-2.34$, $p = .048$, but not among the BPD symptom group ($p = .069$).

Reaction Time. Mean simple and choice reaction times were 261.27 ± 19.21 ms (95% CI [216.97, 305.57]) and 267.32 ± 36.28 ms (95% CI [183.66, 350.98]), respectively, for healthy controls. Mean simple and choice reaction times were 259.07 ± 23.80 ms (95% CI [197.88, 320.26]) and 248.77 ± 26.56 ms (95% CI [180.48, 317.06]), respectively, for BPD symptom participants (Figure 3a). Exploratory repeated measures ANCOVA models revealed no effect of group, $F(1,13)=.117$, $p = .737$, $\eta_p^2 = .046$, or task $F(1,13)=.620$, $p = .445$, $\eta_p^2 = .009$, and the interaction term was not statistically significant $F(1,13)=1.74$, $p = .209$, $\eta_p^2 = .118$. Among participants with BPD symptoms, paired t-tests revealed that choice reaction times were significantly faster than simple reaction times ($t(5)=3.61$, $p = .015$). There was no difference between simple and choice reaction times within the healthy control group ($p = .554$).

Duration Discrimination. Mean duration discrimination capacity scores were 72.78 ± 28.52 ms (simple; 95% CI [7.01, 138.55]) and 149.11 ± 89.32 ms (confound; 95% CI [-56.86, 355.08]) for healthy controls. Mean duration discrimination capacity scores were 78.33 ± 47.40 (simple; 95% CI [-43.54, 200.20]) and 83.33 ± 42.62 ms (confound; 95% CI [-26.25, 192.91]) for participants with BPD symptoms (Figure 3d). Exploratory repeated measures ANCOVAs revealed no effect of group, $F(1,13)=.229$, $p = .641$, $\eta_p^2 = .020$, or task $F(1,13)=.386$, $p = .547$, $\eta_p^2 = .034$, and no interaction $F(1,13)=1.063$, $p = .325$, $\eta_p^2 = .088$. Paired t-tests revealed a significant difference between simple duration discrimination capacity and duration discrimination with a confound within the healthy control group $t(8)=-3.20$, $p = .013$, but not among the BPD symptom group ($p = .660$).

Temporal Order Judgement. Mean temporal order judgment thresholds were 32.15 ± 12.66 ms (simple; 95% CI [2.96, 61.34]) and 36.67 ± 18.40 ms (carrier; 95% CI [-5.76, 79.10]) for healthy controls. Mean temporal order judgment thresholds were 40.88 ± 35.90 (simple; 95% CI [-51.42, 133.18]) and 64.85 ± 49.31 ms (carrier; 95% CI [-61.93, 191.63]) for participants with BPD symptoms (Figure 3e). Exploratory repeated measures ANCOVAs revealed no effect of group, $F(1,12)=.1.83$, $p = .202$, $\eta_p^2=.132$, or task $F(1,12)=.003$, $p = .958$, $\eta_p^2 < .001$, and no interaction $F(1,12)=1.34$, $p = .270$, $\eta_p^2 = .100$. Paired t-tests revealed no significant difference between performance on temporal order judgment and temporal order judgement with a carrier among either subject group (healthy controls: $t(8)=-.488$, $p = .639$; BPD symptoms participants: $t(6)=-1.00$, $p = .363$).

Discussion

This is the first study to compare somatosensory processing measured by vibrotactile psychophysics among individuals with BPD symptoms who engage in NSSI, relative to healthy controls. Somatosensory processing was assessed using a novel device, the CM5, which is thought to reflect the cortical mechanisms underlying sensory processing abilities across several domains (Cortical Metrics, LLC; model CM5). Although this pilot study was not powered for statistical significance testing, the current findings provide initial support regarding the feasibility and tolerability of assessing somatosensory processing among individuals with BPD symptoms who engage in NSSI.

Vibrotactile behavioral data was successfully collected from participants in a total testing time of approximately 30 minutes, and no participants reported finding the paradigm to be aversive. The brevity of psychophysical data collection using the CM5 device allows for greater numbers of participants to be tested across studies of sensory processing (Puts et al., 2013).

Results of the present study suggest that this protocol is also viable among participants with BPD symptoms. Compared to traditional fMRI paradigms that typically focus on pain perception, the CM5 vibrotactile stimulation paradigm is easier and less costly to implement (Puts et al., 2013).

The present study maintained a relatively high retention rate of participants (83.3%), suggesting that further explorations using this paradigm with BPD populations may successfully implement the protocol. Additionally, we successfully consented all participants who were determined eligible via telephone screening. This indicates that larger-scale studies within the same population using similar eligibility criteria should be able to effectively recruit eligible participants. As study inclusion and exclusion criteria were fairly restrictive, the 22.8% enrollment among screened participants suggests these criteria are adequate for use when recruiting from a community setting. Finally, all participants successfully tolerated the sensory testing battery, with none reporting any difficulties understanding or completing the tasks. Collectively, these findings support the feasibility of using the CM5 in populations with BPD symptoms who engage in NSSI.

Regarding the detection threshold task, mean differences were in the expected direction, with healthy control participants exhibiting lower detection thresholds across both tasks than BPD symptom participants. The observed effect size for this difference as a function of participant group and task condition ($\eta_p^2 = .001$) may be characterized as small in magnitude. Exploratory ANCOVA analyses revealed no significant group differences or interactions. The detection threshold task has been suggested as related to feed-forward GABAergic inhibition, and future studies with larger samples may clarify how detection threshold may relate to earlier findings of altered sensory processing in individuals with BPD symptoms who engage in NSSI (Puts et al., 2013).

Regarding the amplitude discrimination task, mean differences were in the expected direction, with healthy control participants performing worse following an adapting stimulus (i.e. participants had more difficulty discriminating between the two vibration stimuli) than BPD symptom participants. The observed effect size for this difference as a function of participant group and task condition ($\eta_p^2 = .051$) may be characterized as moderate in magnitude. Exploratory ANCOVA analyses revealed no significant group differences or interactions. This result is consistent with previous findings in the literature, and suggests that this task warrants follow-up in future studies investigating sensory processing in similar populations (Puts et al., 2014). Amplitude discrimination performance is expected to worsen following a single-site adaptation task, perhaps reflecting lateral inhibitory connections between areas of the brain representing different digits, and fewer of these connections may reduce capacity to discriminate amplitudes (Tannan, Simons, Dennis, & Tommerdahl, 2007; Zhang, Francisco, Holden, Dennis, & Tommerdahl, 2011).

Regarding the reaction time task, mean differences were not in the expected direction, with BPD symptom participants performing faster than healthy control participants on both the simple and choice reaction time tasks. The observed effect size for the difference between ($\eta_p^2 = .118$) may be characterized as moderate in magnitude. Exploratory ANCOVA analyses revealed no significant group differences or interactions, but did indicate that participants with BPD symptoms evinced faster mean choice reaction times than mean simple reaction times. This is contrary to past work showing that choice reaction times tend to be greater than simple reaction times across healthy and clinical populations of all ages (Puts et al., 2013; 2017). The mean difference between the paired tasks was in the expected direction for healthy control participants. The reaction time tasks probe both attentional and sensorimotor components, and

future explorations of reaction time sensory tasks within populations with BPD symptoms should include components that specifically address the role of attention (Puts et al., 2013). Although the role of attention has been investigated in previous studies of pain-related sensory processing in BPD, findings have been mixed, and measures probing the relationship between attention and general somatosensation abilities in this population have been largely absent. BPD often co-occurs with disorders that impact attention (e.g. ADHD), and previous research has demonstrated differences in tactile sensory processing between populations that experience attentional difficulties and healthy controls (Davids and Gastpar, 2005; Puts et al., 2017). Thus, further investigations of sensory processing in individuals with BPD symptoms should incorporate tasks that can distinguish the impact of attention on tactile sensory processing tasks.

Regarding the duration discrimination task, mean differences were in the expected direction, with healthy control participants evidencing faster simple duration discrimination times as compared to the confound task condition times. BPD symptom participants exhibited a similar pattern of responding. The observed effect size for this difference as a function of participant group and task condition ($\eta_p^2 = .088$) may be characterized as moderate in magnitude. Exploratory ANCOVA analyses revealed no significant group differences or interactions. Duration discrimination, or the ability to accurately identify which of two stimuli has a longer temporal duration, is impacted in an illusory manner by increasing the intensity of one of the stimuli (also known as the confound, within the paradigm used in this study; Tommerdahl et al., 2016). Previous studies have found that the confound condition had less of an impact on performance among clinical populations, and the present study evinced similar results in that healthy control participants were significantly impacted by the presence of a confounding stimulus (Tommerdahl et al., 2016).

Regarding the temporal order judgment task, mean differences were in the expected direction, with healthy control participants performing faster than BPD symptom participants across both task conditions. The observed effect size for this difference as a function of participant group and task condition ($\eta^2 = .100$) may be characterized as moderate in magnitude. Exploratory ANCOVA analyses revealed no significant group differences or interactions. In previous investigations of temporal order judgment tasks, healthy controls performed significantly worse in the presence of an illusory conditioning stimulus (the carrier stimulus used in the present paradigm; Puts et al., 2014; Tommerdahl et al., 2016). It has been suggested that temporal order judgment impairments are related to impairments in temporal encoding or local synchrony within clinical populations; these may be areas of interest in work exploring sensory impairments in clinical populations who engage in NSSI (Puts et al., 2014).

Despite notable strengths, including the utilization of an experimental tactile sensory protocol that produces more granular sensory processing data, it is important to note several limitations of the present pilot study. First, the sample size was small and statistical analyses were therefore underpowered. Thus, statistical results (especially null findings) should be interpreted with great caution. Future research with larger samples is needed to more appropriately investigate sensory processing abilities among individuals with BPD symptoms who engage in NSSI. Second, the present study excluded participants with current or former moderate or severe substance use disorders. As BPD often co-occurs with substance use disorders, this exclusion may limit generalizability (Trull et al., 2018). Additionally, increased alcohol consumption has been shown to impact performance on the single-site adaptation condition of the amplitude discrimination task (Nguyen et al., 2012), and including participants with BPD and co-occurring alcohol use disorders may amplify the detection of sensory deficits

related to amplitude discrimination. Third, although the present study endeavored to recruit participants between ages 18 and 45, the mean sample age was approximately 24. This further restricts generalizability, and future research would benefit from examining similar outcomes across a range of ages and developmental trajectories. Fourth, sex distributions were uneven across groups such that more males than females were included in the BPD symptom group, whereas males were underrepresented in the healthy control group. Males have been found to exhibit faster simple reaction times than females across the lifespan (Dykiert, Der, Starr, & Deary, 2012), and future research would benefit from stratifying study samples by sex. Finally, although these tasks are thought to reflect aspects of inhibitory function, further work is needed to clarify the cortical mechanisms underlying task performance among individuals with BPD (Puts et al., 2011; Puts et al., 2017). These tasks are analogues of neurophysiological functioning, and future investigations should focus on investigating the relationship between vibrotactile tasks and their neural underpinnings (Puts et al., 2017).

Future work investigating NSSI behaviors and BPD symptomatology using the present protocol has the potential to clarify mechanisms underlying altered somatosensory processing in individuals with BPD. In previous explorations of sensory processing mechanisms related to BPD, altered pain processing has been connected to general BPD symptomatology (but not NSSI behaviors characteristic of the disorder; Schmahl et al., 2004; Pavony & Lenzenweger, 2014). Somatosensory differences unique to individuals with BPD symptoms that engage in NSSI may partially account for the robust findings of reduced pain sensitivity in earlier studies. As individuals with BPD who engage in NSSI have not traditionally been examined separately from those who do not engage in NSSI, previous findings documenting a lack of general sensory processing differences between BPD subjects and healthy controls may have been influenced by

the lack of accounting for co-occurring NSSI. Additionally, studies comparing pain perception and exteroception among individuals with BPD have not employed methods capable of disentangling pain-specific from general tactile sensory processes (Schmahl et al., 2004; Pavony & Lenzenweger, 2014). Future investigations should include measurements that assess processes specific to pain and tactile somatosensation, separately. Lastly, pain-related sensory processing in BPD has previously been linked to a decrease in negative affectivity following pain induction (indicating emotional regulation in response to painful stimuli), and this effect has been shown to be amplified in the presence of stress (Bohus et al., 2000; Reitz et al., 2015). Future work should investigate the relationship between tactile sensory stimulation and emotion regulation, as sensory pathways that reduce negative affect following pain stimulation may also be invoked following tactile stimulation. Indeed, contemporary conceptual models of NSSI posit that its primary function is emotion regulation (Nock, 2010), and sensory pathways that may be driving this process warrant further investigation.

Though many advances have been made over the last few decades in BPD and sensory processing research, mechanisms underlying relations between BPD, tactile sensory perception, and affect regulation in NSSI remain largely unexplored. Further research is needed to clarify the relationship between altered sensory processing and NSSI, which in turn may aid the development of clinical interventions to help individuals with BPD employ more adaptive methods of emotion regulation. Additionally, self-harm and sensory dysregulation are not specific to BPD alone. Autism Spectrum Disorder is characterized by similar pain perception and sensory perception differences, and investigating altered sensory capabilities and self-harm behaviors across different diagnoses may further clarify the ways in which they interrelate. Previous research on self-injurious behaviors indicates that individuals who engage in NSSI tend

to use multiple methods, and that these methods vary in their level of risk (Nock, 2010). Further work is needed to clarify whether specific deficits in tactile sensory processing relate to method of self-injury, as this information could aid in the identification of individuals most likely to engage in riskier forms of self-injury (e.g., cutting).

In summary, results of the current study represent an initial, yet important step towards better understanding the role of somatosensory processing among individuals with BPD. No previous research has examined sensory processing among individuals with BPD symptoms who engage in NSSI using a vibrotactile psychophysical device, and these findings provide initial evidence that this paradigm can be successfully implemented among participants who engage in self-injurious behaviors. Future research using this paradigm has potential to explicate differences in sensory processing between individuals that engage in NSSI and those that do not. Identifying sensory deficits associated with risk for engaging in NSSI behaviors would facilitate the design of targeted interventions to treat NSSI across a spectrum of disorders.

Tables

Table 1

Skewness and kurtosis values for primary predictor and primary outcome variables

Variable	<i>N</i>	Skewness	Kurtosis
Simple Reaction Time (ms)	15	0.53	-.598
Choice Reaction Time (ms)	15	0.43	0.22
Static Detection Threshold (μm)	15	1.02	-0.55
Dynamic Detection Threshold (μm)	15	-0.39	-0.83
Amplitude Discrimination, no adaptation (μm)	15	-0.28	-0.92
Amplitude Discrimination, single-site adaptation(μm)	15	0.77	0.73
Duration Discrimination (ms)	15	1.42	2.45
Duration Discrimination, confound (ms)	15	1.81	3.77
Temporal Order Judgement (ms)	15	2.19	6.20
Temporal Order Judgement, with carrier (ms)	15	1.75	3.56
Past-Year NSSI	6	1.76	1.97

Table 2

Sociodemographic information and baseline clinical data

	Healthy Control Group M (SD)	BPD Symptom Group M (SD)
N	9	6
Age	21.96 ± 2.85	25.6 ± 3.7
Gender		
Male	3 (33.3%)	4 (66.7%)
Race		
White	5 (55.6%)	4 (66.7%)
Non-White	4 (44.4%)	2 (33.3%)
Education		
Partial College Training	5 (55.5%)	5 (83.3%)
College/University Graduate	3 (33.3%)	1 (16.7%)
Graduate/Professional	1 (11.1%)	0 (0.0%)
BPD Symptom Count	0.44 ± 0.73	4.83 ± 2.04**
Past-Year NSSI	N/A	31.2 ± 19.65
BMI	23.03 ± 1.96	22.45 ± 2.46

Note. * $p < .05$; ** $p < .01$.

Table 3

Bivariate and point-serial correlations between variables of primary interest

Variable	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1. Age	-	-.10	.32	.66**	-.27	-.05	-.19	-.12	-.05	.28	-.07	.41*	.05	-.14	.12	-.36	.24
2. Gender		-	-.33	.09	-.39	-.32	-.04	.26	.42	-.36	-.39	-.22	-.09	-.11	.01	-.14	-.39
3. Race			-	.29	-.13	-.20	.20	-.32	-.35	.45	.03	.01	-.03	.38	.52*	-.03	.48*
4. Education				-	-.34	-.19	-.33	-.06	.00	.23	-.25	.45*	-.21	-.27	-.19	-.26	.22
5. BPD Symptom Count					-	.71**	-.15	-.07	-.29	.14	.12	-.04	-.01	-.07	-.43*	.15	.12
6. Past-Year NSSI Frequency						-	-.20	-.05	-.17	.01	.00	-.07	.06	-.05	-.42*	-.01	.17
7. BMI							-	.13	.13	.32	.13	-.23	-.14	.15	.34	-.18	-.10
8. Simple Reaction Time								-	.58**	.05	-.20	.07	-.36	-.16	-.04	-.21	-.39*
9. Choice Reaction Time									-	-.14	-.05	-.09	-.32	-.35	.04	-.13	-.54**
10. Static Detection Threshold										-	.18	.20	-.29	-.12	.29	-.20	.20
11. Dynamic Detection Threshold											-	.03	.05	.00	.27	.31	.16
12. Amplitude Discrimination, no adaptation												-	.15	-.20	-.10	-.33	.16
13. Amplitude Discrimination, single-site adaptation													-	.40*	-.14	-.02	.26
14. Duration Discrimination														-	.25	.13	.35
15. Duration Discrimination, confound															-	.05	.19
16. Temporal Order Judgement																-	.10
17. Temporal Order Judgement, with carrier																	-

Note. * $p < .05$; ** $p < .01$.

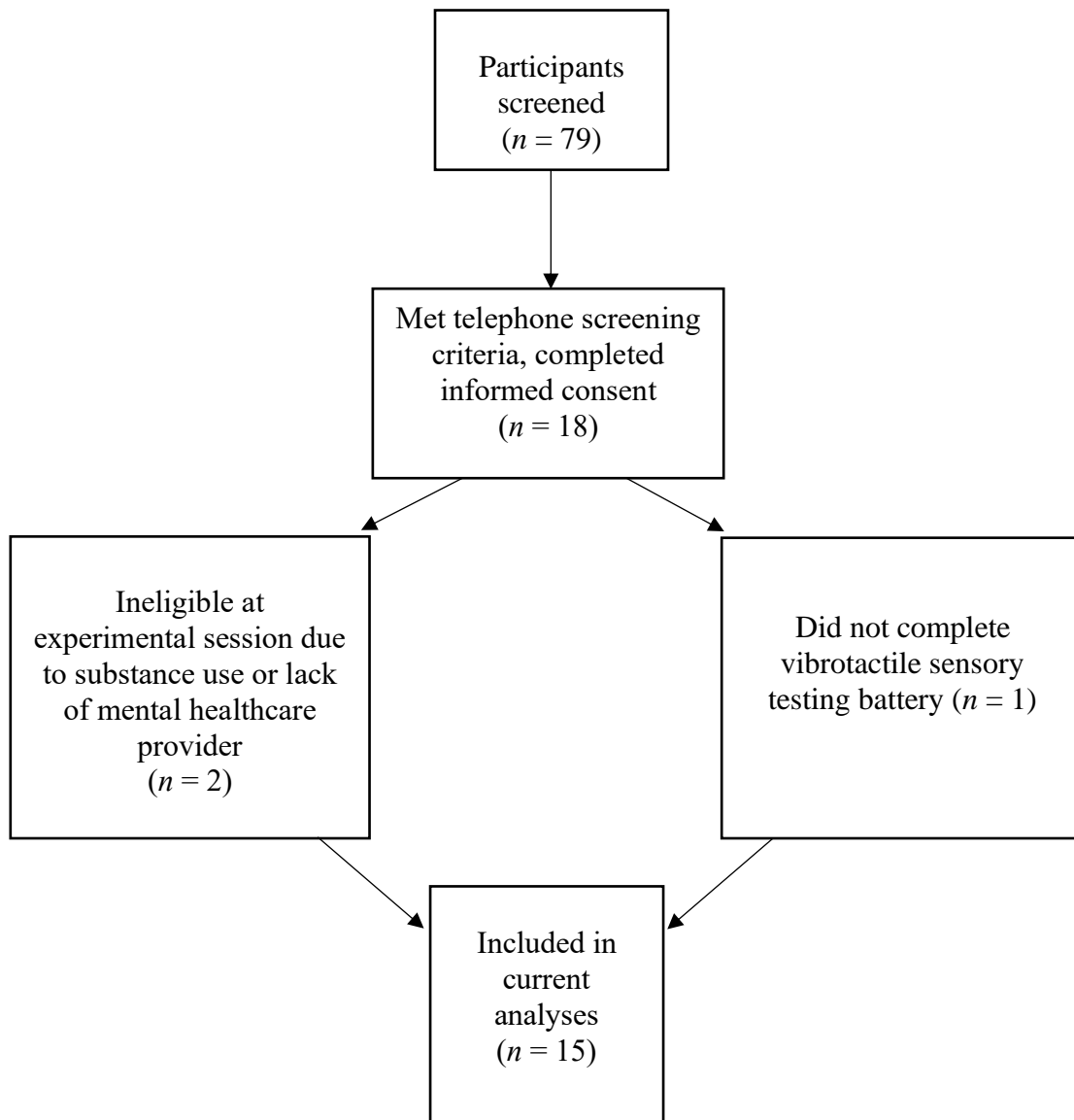


Figure 1. Flowchart of Participant Recruitment.

Recruitment	Telephone Screening		In-Person Experimental Session	Baseline Measures
Responded to an ad for a study investigating stress responses in everyday life	Screened for inclusion and exclusion criteria	Eligible Participants: Scheduled for an in-lab study visit	Completed informed consent, participants were assessed for DSM-5 diagnoses and completed tasks related to the larger study on stress and suicidality	Demographics, BMI, NSSI behaviors, sensory testing battery

of Study Procedures.

Figure 2. Timeline



Figure 3. Psychophysical task results. Graphs display means for healthy control and BPD symptom participants broken down by psychophysical task condition.

Appendix A

Structured Clinical Interview for DSM-5 Personality Disorders – BPD Screening Module

Instructions

These questions are about the kind of person you generally are; that is, how you have usually felt or behaved over the past several years. Circle “YES” if the question completely or mostly applies to you or “NO” if the question does not apply to you. If you do not understand a question, leave it blank.

77.	Have you become frantic when you thought that someone you really cared about was going to leave you?	<i>NO</i>	<i>YES</i>	PQ80
78.	Do relationships with people you really care about have a lot of extreme ups and downs.	<i>NO</i>	<i>YES</i>	PQ81
79.	Does your sense of who you are often change dramatically?	<i>NO</i>	<i>YES</i>	PQ82
80.	Are you different with different people or in different situations, so that you sometimes don't know who you really are?	<i>NO</i>	<i>YES</i>	PQ83
81.	Have there been lots of sudden changes in your goals, career plans, religious beliefs, and so on?	<i>NO</i>	<i>YES</i>	PQ84
82.	Have there been lots of sudden changes in the kinds of friends you have or in your sexual identity?	<i>NO</i>	<i>YES</i>	PQ85
83.	Have you often done things impulsively?	<i>NO</i>	<i>YES</i>	PQ86
84.	Have you tried to hurt or kill yourself or threatened to do so?	<i>NO</i>	<i>YES</i>	PQ87
85.	Have you ever cut, burned, or scratched yourself on purpose?	<i>NO</i>	<i>YES</i>	PQ88
86.	Does your mood often change in a single day, based on what's going on in your life?	<i>NO</i>	<i>YES</i>	PQ89
87.	Do you often feel empty inside?	<i>NO</i>	<i>YES</i>	PQ90
88.	Do you often have temper outbursts or get so angry that you lose control?	<i>NO</i>	<i>YES</i>	PQ91
89.	Do you hit people or throw things when you get angry?	<i>NO</i>	<i>YES</i>	PQ92
90.	Do even little things get you very angry?	<i>NO</i>	<i>YES</i>	PQ93
91.	When you get very upset, do you get suspicious of other people or feel disconnected from your body or that things are unreal?	<i>NO</i>	<i>YES</i>	PQ94

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