

Central and Peripheral Physiological Responses to Decision Making in Hoarding Disorder

Hannah Levy¹, Adam Naples², Sarah Collett¹, James McPartland³, and David Tolin⁴

¹Hartford Hospital

²Yale University

³Yale

⁴Hartford Hospital Institute of Living

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Abstract

Individuals with hoarding disorder (HD) have difficulty parting with personal possessions, which leads to the accumulation of excessive clutter. According to a proposed biphasic neurobiological model, HD is characterized by blunted central and peripheral nervous system activity at rest and during neutral (non-discarding) decisions, and exaggerated activity during decision-making about discarding personal possessions. Here, we compared the error-related negativity (ERN) and psychophysiological responses (skin conductance, heart rate and heart rate variability, and end tidal CO₂) during neutral and discarding-related decisions in 26 individuals with HD, 37 control participants with anxiety disorders, and 28 healthy control participants without psychiatric diagnoses. We also compared alpha asymmetry between the HD and control groups during a baseline resting phase. Participants completed a series of Go/No Go decision-making tasks, one involving choosing certain shapes (neutral task) and the other involving choosing images of newspapers to imaginarily “discard” (discarding task). Contrary to hypotheses, there were no group differences in the ERN or any psychophysiological measures. Alpha asymmetry at rest did not differ between groups. The findings suggest that the ERN and psychophysiological responses may not differ in individuals with HD during simulated discarding decisions relative to control participants, although the null results may be explained by methodological challenges in using Go/No Go tasks as discarding tasks. Future replication and extension of these results will be needed using ecologically valid discarding tasks.

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Hannah C. Levy¹

Adam J. Naples^{2, 3}

Sarah Collett¹

James C. McPartland^{2, 3}

David F. Tolin^{1, 4}

¹Anxiety Disorders Center, Institute of Living, Hartford, CT, USA

²Yale Child Study Center, Yale School of Medicine, New Haven, CT, USA

³Center for Brain and Mind Health, Yale School of Medicine, New Haven, CT, USA

⁴Yale University School of Medicine

Author Note

Correspondence concerning this article should be addressed to Hannah Levy, Anxiety Disorders Center, Institute of Living/Hartford Hospital, 200 Retreat Avenue, Hartford, CT 06106. Tel.: 860-545-7847. Fax: 860-545-7105. Email: hannah.levy@hhchealth.org.

Author email addresses: Adam Naples, adam.naples@yale.edu; Sarah Collett, sarah.collett@hhchealth.org; James McPartland, james.mcpartland@yale.edu; David Tolin, david.tolin@hhchealth.org

Abstract

Individuals with hoarding disorder (HD) have difficulty parting with personal possessions, which leads to the accumulation of excessive clutter. According to a proposed biphasic neurobiological model, HD is characterized by blunted central and peripheral nervous system activity at rest and during neutral (non-discarding) decisions, and exaggerated activity during decision-making about discarding personal possessions. Here, we compared the error-related negativity (ERN) and psychophysiological responses (skin conductance, heart rate and heart rate variability, and end tidal CO₂) during neutral and discarding-related decisions in 26 individuals with HD, 37 control participants with anxiety disorders, and 28 healthy control participants without psychiatric diagnoses. We also compared alpha asymmetry between the HD and control groups during a baseline resting phase. Participants completed a series of Go/No Go decision-making tasks, one involving choosing certain shapes (neutral task) and the other involving choosing images of newspapers to imaginarily “discard” (discarding task). Contrary to hypotheses, there were no group differences in the ERN or any psychophysiological measures. Alpha asymmetry at rest did not differ between groups. The findings suggest that the ERN and psychophysiological responses may not differ in individuals with HD during simulated discarding decisions relative to control participants, although the null results may be explained by methodological challenges in using Go/No Go tasks as discarding tasks. Future replication and extension of these results will be needed using ecologically valid discarding tasks.

Keywords : hoarding disorder; error-related negativity; psychophysiological responses; discarding

Central and Peripheral Physiological Responses to Decision Making in Hoarding Disorder

Hoarding disorder (HD) is characterized by difficulty discarding personal possessions, which leads to the accumulation of excessive clutter (American Psychiatric Association, 2013). HD is associated with significant functional impairment. Compared to patients with related mental health problems such as obsessive-compulsive disorder (OCD), patients with HD report significantly worse overall functioning and quality of life (Saxena et al., 2011). A systematic review similarly concluded that individuals with HD experience greater impairment in various domains of functioning relative to control groups (Ong et al., 2015).

Unfortunately, treatment options for HD are limited. Cognitive-behavioral therapy (CBT) is efficacious for HD (Steketee et al., 2010; Tolin et al., 2019), but results are modest. Meta-analytic research suggests that only 35% of patients with HD who receive CBT achieve clinically significant change (a measure of remission status) (Tolin et al., 2015). To address this problem, research has focused on identifying neurobiological mechanisms of HD that may inform novel treatment development. A proposed biphasic neurobiological model of HD (Tolin, 2023) posits that HD is characterized by blunted central nervous system (CNS) and peripheral nervous system (PNS) activity at rest or during neutral (non-discarding) tasks, and exaggerated CNS and PNS activity during decision-making about discarding personal possessions.

Some evidence points to a baseline under-engagement of CNS processes in individuals with HD. An early positron emission tomography (PET) study, which predates the DSM-5 diagnosis of HD, found that OCD patients with prominent hoarding symptoms exhibited significantly lower activity in posterior cingulate gyrus and cuneus relative to healthy control participants during a task-free resting state (Saxena et al., 2004). A more recent functional magnetic resonance imaging (fMRI) study (Sunol et al., 2019) found that individuals with HD demonstrated decreased activity in dorsolateral prefrontal cortex (dlPFC), dorsomedial prefrontal cortex (dmPFC), and precentral gyrus during error processing in a Go/No Go task relative to individuals with OCD and healthy control participants, though orbitofrontal cortex (OFC) activity was enhanced. Other fMRI research has similarly shown attenuated activity in frontal regions, including the anterior cingulate

cortex (ACC) and insula, during emotionally-neutral decision-making in HD participants relative to clinical and nonclinical control groups (Stevens et al., 2020; Tolin et al., 2012). In contrast to these results, it should be noted that Hough et al. (2016) reported greater activation of frontal regions (ACC and dlPFC) during an emotionally neutral (non-discarding) Go/No Go task in participants with HD, compared to healthy controls and individuals with OCD.

Conversely, when making emotionally salient decisions about discarding personal possessions during fMRI, relative to healthy control participants and those with OCD, individuals with HD demonstrate excessive activity in the ACC and insula (Stevens et al., 2020; Tolin et al., 2012). Further evidence of exaggerated responding comes from studies of PNS response. When making personally relevant decisions about discarding their own possessions vs. when deciding whether to discard matched control items (“experimenter owned” possessions, which were items donated by study staff), participants with HD demonstrated greater heart rate, greater skin conductance, and increased hyperventilation as indicated by lower end tidal CO₂ (ETCO₂) (Levy, Nett, & Tolin, 2019).

The present study aimed to expand on these prior studies, which collectively suggest a biphasic abnormality, by measuring CNS and PNS activity during a neutral task and during a simulated decision-making task about possessions. For CNS measurement, we used electroencephalography (EEG) because it captures ongoing neural activity with a temporal resolution that is superior to fMRI, thus allowing us to examine moment-to-moment changes in brain activity that may be specific to discarding decisions. We focused first on error-related negativity (ERN), a negative event-related potential that is generated by the ACC when an individual detects that they have made an error, or when an error is likely. Consistent with prior studies of CNS responses (Stevens et al., 2020; Sunol et al., 2019; Tolin et al., 2012), during non-discarding-related tasks, the ERN is significantly lower in individuals with HD relative to individuals with OCD and healthy control participants (Baldwin et al., 2019; Mathews et al., 2016). In a sample of undergraduate student participants, hoarding symptoms predicted greater ERN amplitudes for discarding-related decisions but not emotionally neutral decisions (Baldwin, Whitford, & Grisham, 2016). We predicted that individuals with HD would demonstrate greater ERN during discarding decisions, and lower ERN during emotionally neutral decisions, compared to anxious and healthy control groups, and that the ERN during simulated discarding decisions would predict the severity of HD symptoms.

We also assessed resting state alpha asymmetry, or the difference between left and right alpha wave activity in the frontal regions of the brain. Relatively greater left vs. right alpha activity is commonly associated with approach motivation (Harmon-Jones, Peterson, & Harris, 2009; Harmon-Jones et al., 2004), whereas relatively greater right vs. left alpha is thought to reflect withdrawal/avoidance motivation (Coan, Allen, & Harmon-Jones, 2001). Consistent with these results, greater right alpha is associated with psychiatric conditions that are characterized by withdrawal and avoidance, such as depression [for a review, see Coan and Allen (2004)]. We are not aware of any prior research assessing alpha asymmetry in patients with HD; however, based on evidence from related psychiatric conditions such as depression, we predicted that the HD group would demonstrate greater right vs. left alpha asymmetry during the baseline resting period.

For PNS activity, we compared psychophysiological responses among HD participants and the control groups. Specifically, we measured ETCO₂, heart rate (HR) and heart rate variability (HRV), and skin conductance. Thus, this study expands the findings of Levy, Nett and Tolin (2019) who did not use a control group. We predicted that the HD group would demonstrate greater psychophysiological activation for simulated discarding decisions, and lower psychophysiological activity during emotionally neutral decisions, relative to the control groups.

Method

Participants

Participants were 26 adults with a primary diagnosis of HD, 37 adults with a primary diagnosis of a DSM-5 (American Psychiatric Association, 2013) anxiety disorder (ANX), and 28 adult healthy control participants without psychiatric disorders (HC). Participants were recruited from the regular patient flow at an anxiety

disorders specialty clinic, through a registry of individuals who had previously consented to be contacted about research opportunities at the clinic, and through media advertisements and flyers posted throughout the surrounding community.

All participants were required to be fluent in English, be right-handed, and have no history of anoxic or traumatic brain injury with loss of consciousness greater than five minutes and no history of neurocognitive disorder that may interfere with the ability to understand the study tasks and provide informed consent. Any history of psychotic disorder or bipolar disorder, current substance use disorder, and serious suicide risk were also exclusionary.

Inclusion criteria for the HD group were a primary diagnosis of HD of at least moderate severity as indicated by a Clinical Global Impression (CGI) (Guy, 1976) rating of 4 or greater. Inclusion criteria for the ANX group were a primary diagnosis of a DSM-5 anxiety disorder of at least moderate severity as indicated by a CGI rating of 4 or greater. For both clinical groups, comorbid conditions were permitted as long as they were secondary to the primary diagnosis. Antidepressants, stimulants, and benzodiazepines were permitted at stable dosages for a minimum of eight weeks. All other psychiatric medications were excluded. For participants taking benzodiazepines and stimulants, a 24-hour “washout” of these medications was required prior to the study with the prescriber’s approval. Inclusion criteria for the HC group were no past or current psychiatric disorders or mental health treatment.

As shown in Table 1, although we attempted to match the control groups to the HD group for age and sex assigned at birth, we had significant age differences. As such, we controlled for age in all study analyses. We note that we assessed sex assigned at birth and not gender identity to be consistent with the National Institute of Mental Health National Data Archive (NDA), in order to facilitate data transfer to the NDA (a requirement of the grant). As expected, the HD group scored significantly higher than did the control groups on the *Saving Inventory-Revised* (SI-R), a measure of hoarding severity.

Table 1

	Total Sample, % (N)	HD Group, % (n)	ANX Group, % (n)	HC Group, % (n)	Group Comparison, χ^2 or F , p
Age, M (SD)	48.36 (13.03)	56.08 (7.76)	43.16 (13.68)*	48.07 (12.88)*	8.82, <.001
Female sex assigned at birth	72.5 (66)	84.6 (22)	67.6 (25)	67.9 (19)	2.67, .263
Race	4.4 (4) 1.1 (1)	3.8 (1) 0 (0) 92.3	0 (0) 2.7 (1) 91.9	10.7 (3) 0 (0)	13.40, .340
Black/African- American Asian	90.1 (82) 1.1 (1)	(24) 0 (0) 0 (0)	(34) 0 (0) 2.7 (1)	85.7 (24) 4.2 (1)	
White American Indian/Alaska Native More than one race	(1) (1) 1.1 (1)	3.8 (1) 0 (0)	0 (0) 2.7 (1)	0 (0) 0 (0) 0 (0)	
Unknown/not reported Other					
Hispanic/Latinx	9.9 (9)	0 (0)	8.1 (3)	21.4 (6)*	7.17, .028
SI-R, M (SD)	25.71 (22.05)	56.46 (11.65)	16.73 (10.25)*	9.04 (6.77)*	184.83, <.001
Total Clutter	10.16 (10.42)	24.27 (6.07)	6.11 (5.57)*	2.43 (3.17)*	142.19, <.001
Saving	8.44 (7.20)	18.23 (4.00)	5.57 (3.83)*	3.14 (2.34)*	146.38, <.001
Acquiring	7.11 (5.76)	13.96 (4.67)	5.05 (3.84)*	3.46 (2.46)*	62.17, <.001

Demographic and Clinical Characteristics and Comparisons Between Groups

Note . HD = Hoarding disorder. ANX = Anxious control. HC = Healthy control. SI-R = Saving Inventory-Revised.

*significantly different from the HD group, $p < .05$

Measures

Diagnostic assessment. Diagnoses were determined using the *Diagnostic Interview for Anxiety, Mood, and Obsessive-Compulsive and Related Disorders* (DIAMOND) (Tolin et al., 2018), a structured diagnostic interview based on the DSM-5 (American Psychiatric Association, 2013) that has demonstrated good reliability and validity estimates for anxiety disorders and HD (e.g., adequate inter-rater reliability for anxiety disorders [$\kappa = 0.73$] and HD [$\kappa = 0.86$]) (Tolin et al., 2018). Interviewers completed a comprehensive training program in administration and scoring of the DIAMOND (www.diamondinterview.org), and were trained to criterion ($\kappa = 0.80$ against an expert rater) prior to administering the interview. Interviewers were licensed psychologists or Bachelor’s-level clinical research assistants supervised by licensed psychologists. After administering the DIAMOND, the clinician rated overall global illness severity using the CGI, a 7-point clinician-administered rating of overall symptom severity ($1 = Normal$; $7 = Extreme$).

Self-report measures. Self-reported HD severity was assessed using the 23-item *Saving-Inventory-Revised* (SI-R) (Frost, Steketee, & Grisham, 2004), which has demonstrated adequate reliability as well as strong convergent and discriminant validity. Items are scored on a 5-point Likert scale ($0 = None$; $4 = Almost All/Complete$), with higher scores indicating more severe hoarding symptoms. The SI-R yields a total score as well as three subscales (clutter, difficulty discarding, and acquiring).

Psychophysiological Assessment

We used the BIOPAC MP150 system (BIOPAC System, Inc., Goleta, CA), a modular data acquisition and analysis system that is widely used in psychophysiological research, to assess psychophysiological activation, alpha asymmetry, and the ERN. We used AcqKnowledge software to filter and extract data.

Psychophysiological activation. The following measures were assessed during a 5-minute baseline resting phase and throughout the discarding and neutral tasks. We assessed skin conductance level (SCL) through a constant voltage of 0.5 V across two electrodes placed on the first and second fingers of the left hand. The total number of skin conductance responses (SCRs), which reflect the peaks in the SCL waveform, were extracted along with mean SCL. Heart rate variability (HRV) and heart rate (HR) data were collected via electrocardiogram (ECG) leads attached to both the left and right wrists, as well as the left ankle. ETCO₂ was collected through nasal cannula and was measured in real time using the AcqKnowledge software rate calculation function. This function allowed for breath-by-breath measurement of ETCO₂ percentage which then we statistically transformed to mmHg.

ERN . EEG data was recorded at 2000hz from six electrodes [‘Fz’, ‘O1’, ‘F3’, ‘O2’, ‘F4’, ‘Pz’] with a linked mastoid reference. All EEG post processing was conducted using the MNE software package (Gramfort et al., 2013). Data were bandpass filtered from 1 to 17Hz and EEG was segmented from 500ms before to 350ms after the commission of a response and baseline corrected from mean activity in the -500 to -100ms pre-response. Epochs with activity greater than 125mv were excluded for artifact. The ERN was measured as the difference between incorrect and correct responses at electrodes F3, Fz, & F4 50 to 150ms post response in line with prior literature (Gehring et al., 2018; Larson et al., 2010; Meyer, 2016; Meyer et al., 2020; Riesel, 2019) and confirmed with visual inspection of grand averaged waveforms.

Resting state alpha asymmetry . Alpha asymmetry was assessed during the baseline resting phase. Baseline EEG was segmented into 1-sec epochs. Artifact detection was the same as for ERN analyses. Artifact-free segments were decomposed into the frequency domain using multitaper fast fourier transform (FFT) implemented in the MNE software package. Frontal asymmetry indices were calculated by subtracting the natural log of the power of the left hemisphere electrode from that of the homologous right hemisphere electrode ($\ln[\text{right (F4)}] - \ln[\text{left (F3)}]$).

Quality control . To minimize artifacts, participants were asked not to move during the study other than to press the appropriate button on the Go/No Go tasks (see below). They were closely observed by a research assistant throughout the study. Any movements that occurred were recorded on a testing form with the specific time that they occurred. If artifacts appeared in the waveform at those times, the sections of the waveform that included the artifact were excluded from the analyses. To ensure reliable data for the EDA analyses, prior to starting the tasks, we asked participants to hold their breath for a few seconds to verify that the signal responded to the breath-holding (EDA waveform should increase with breath-holding). Prior to starting the tasks, we visually inspected the ECG waveform to ensure that QRS peaks were being recorded properly. Additionally, during application of the EEG cap, each electrode was abraded (via a Q-tip) and re-jelled with abrasive electrolyte-gel up to three times, or until impedances as determined by an electrode impedance checker were less than 5 k Ω . The testing room in which the study took place was regulated at a temperature ranging between 71°F-73°F in order to ensure quality data collection.

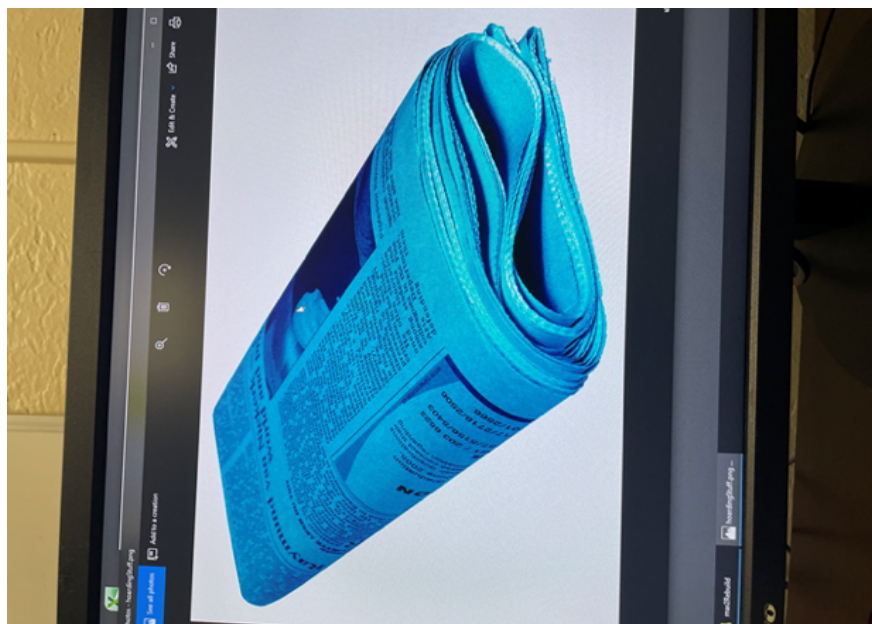
For HRV, we applied a band pass filter (low frequency cutoff = 1 Hz; high frequency cutoff = 35 Hz; QRS peak threshold = 0.5 mV, which was adjusted as needed depending on the height of individual participants' QRS peaks). For EDA, we first applied a low pass filter (1 Hz). The SCR threshold level was set at 0.02 microsiemens.

Tasks

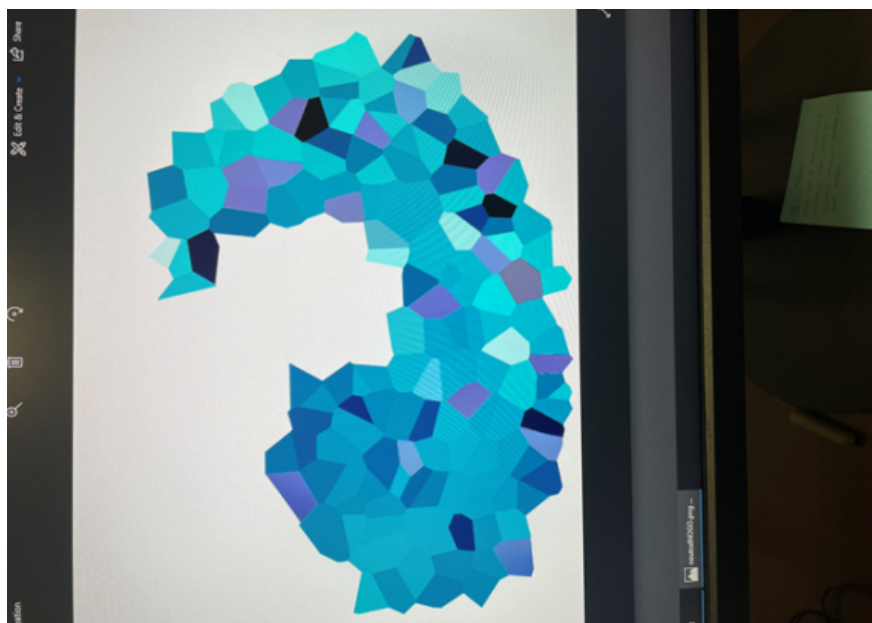
Discarding task . We modeled the discarding task from prior research (Baldwin, Whitford, & Grisham, 2016) in which participants were asked to imagine that pictures of newspapers displayed on the screen belonged to them. They were told: "Newspapers can contain important information, but it's also important to declutter your home. Therefore, we want you to get rid of some of your newspapers." Pictures of various newspapers were presented (see Figure 1), and participants were asked to select only the newspapers containing text (vs. pictures and text, the No Go distractor) to discard (the Go target) via button press.

The targets and distractors were counterbalanced across participants. Trials began with (a) a central fixation crosshair presented for 800-1000ms followed by (b) either a target or a distractor image presented for 112ms followed by (c) a 2000ms response period. Participants were instructed to respond as quickly as possible while remaining accurate in their responses. EEG was segmented to the onset of participant responses. Go and No Go trials were presented at a ratio of 75:25, respectively. After the first 20 trials of only No Go stimuli, Go and No Go pictures were presented at random in blocks of 300 trials each (75 No Go trials), lasting approximately three minutes per block. Prior research has established that the ERN can be reliably measured with only 14 trials and similar published tasks (Baldwin, Whitford, & Grisham, 2016) reported error rates > 70%.

It should be noted that we modified the visual appearance of the newspapers from the Baldwin, Whitford and Grisham (2016) task in order to make the task more challenging. In the original Baldwin study, red (Go target) and blue (No Go distractor) newspapers were used. In our study, we used only blue newspapers, some of which had text only (Go target) vs. pictures and text (No Go distractor).



Emotionally neutral task. As in the Baldwin, Whitford and Grisham (2016) study, we used colored shapes for the neutral (non-discarding) task. Participants were asked to choose blue shapes containing lighter colors (Go target) vs. darker colors (No Go distractor; see Figure 2). These shapes were matched in overall color composition and luminance to those in the discarding task (see above) and participants were encouraged to respond as quickly and accurately as possible.



Procedure

All study procedures were approved by the hospital's Institutional Review Board. Prior to completing

any study procedures, participants provided written informed consent. They then completed a series of questionnaires and the DIAMOND. BIOPAC system sensors were then placed, and participants completed the baseline resting period followed by the two tasks in counterbalanced order. Participants received \$50 for their participation.

Statistical Analyses

As explained above, we controlled for age in the analyses. To test the prediction that the HD group would demonstrate greater ERN during simulated discarding decisions relative to emotionally neutral decisions as compared to the control groups, we used a 3 (group) x 2 (task: ERN during the discarding task vs. neutral task) mixed analysis of covariance (ANCOVA), controlling for age. To test the prediction that the HD group would demonstrate greater right vs. left alpha asymmetry, we used 1-way ANCOVA, controlling for age. For our prediction that the HD group would demonstrate greater psychophysiological activity during the simulated discarding task relative to the neutral task compared to the control groups, we used 3 (group) x 2 (task: ETCO₂, SCL, HRV, and HR during the discarding task vs. neutral task) mixed ANCOVAs, controlling for age. Finally, we used hierarchical multiple regression to test the prediction that the ERN during discarding decisions would predict SI-R scores, controlling for age.

Power Analysis

We conducted an *a priori* power analysis using G*Power 3 (Faul et al., 2007) to determine adequate sample size. At $\alpha = .05$ and 80% power, a total sample size of 42 would be needed to detect a medium effect ($f = 0.25$) for the between-groups comparisons of ERN, ETCO₂, SCL, HRV, and HR.

Results

Group Comparisons

ERN. There were no main effects of group, $F(2, 75) = 0.29$, $p = .751$, $\eta^2_p = 0.01$ or task, $F(1, 75) = 0.09$, $p = .769$, $\eta^2_p = 0.00$ for the ERN. There was no significant group x time interaction, $F(2, 75) = 0.66$, $p = .519$, $\eta^2_p = 0.02$. Contrary to hypotheses, these results indicated no differences in the ERN between the simulated discarding and neutral tasks, and no differences between the HD and control groups. See Table 2 for group means and standard deviations and Figure 3 for grand average waveforms depicting ERN difference waves (error – correct) waveforms for the neutral and discarding tasks. See Table S1 in the Supplement for estimated marginal means controlling for age and 95% confidence intervals.

Table 2

Means and Standard Deviations of Psychophysiological Measures

Measure	HD group	HD group	ANX group	ANX group	HC group	HC group
	Discarding, <i>M</i> (<i>SD</i>)	Neutral, <i>M</i> (<i>SD</i>)	Discarding, <i>M</i> (<i>SD</i>)	Neutral, <i>M</i> (<i>SD</i>)	Discarding, <i>M</i> (<i>SD</i>)	Neutral, <i>M</i> (<i>SD</i>)
ERN	-1.54 (3.38)	-2.14 (3.96)	-1.56 (2.34)	-2.31 (2.92)	-1.59 (2.11)	-2.92 (2.94)
Alpha asymmetry (baseline only)	-0.01 (0.02)	—	-0.01 (0.03)	—	-0.02 (0.03)	—
ETCO ₂	35.80 (17.76)	35.43 (17.62)	39.40 (16.17)	40.18 (17.20)	32.51 (17.95)	32.48 (18.09)
HRV	26.04 (12.47)	23.91 (13.34)	31.84 (19.34)	30.00 (16.71)	33.38 (25.08)	35.79 (35.81)
Heart rate	72.34 (10.45)	72.81 (10.90)	73.66 (11.89)	73.41 (11.51)	68.89 (8.50)	68.82 (8.48)
SCL	1.75 (1.56)	1.94 (1.54)	2.60 (1.80)	2.82 (1.94)	2.28 (1.87)	2.34 (1.81)
SCR	11.27 (8.78)	13.41 (9.48)	15.55 (9.88)	16.90 (11.48)	12.32 (7.83)	13.05 (8.47)

Note . HD = Hoarding disorder. ANX = Anxious control. HC = Healthy control. ERN = Error-related

negativity. ETCO_2 = end-tidal

CO_2 . HRV = Heart rate variability. SCL = Skin conductance level. SCR = Skin conductance response

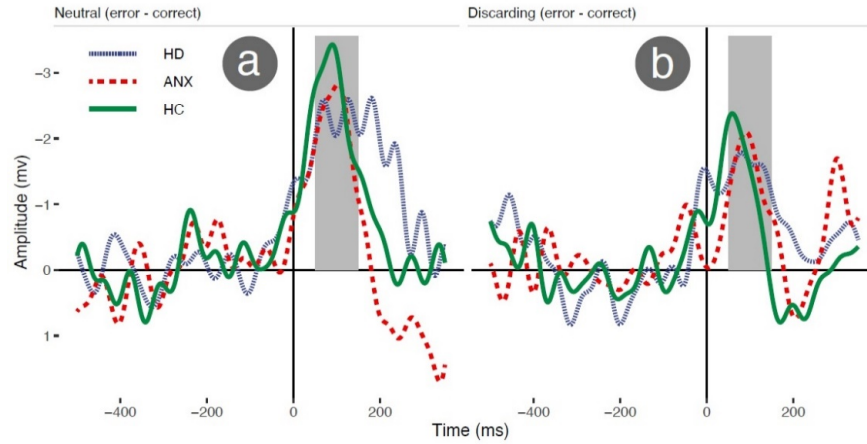


Figure 3. Grand average waveforms depicting ERN difference waves (error – correct) waveforms for neutral and discarding tasks. The left waveform depicts the neutral task, and the right waveform depicts the discarding task. The temporal region (50-150ms) where the mean ERN is measured is demarcated by the grey rectangle.

Alpha asymmetry. There were no significant group differences in alpha asymmetry, $F(2, 81) = 2.43$, $p = .094$, $\eta^2_p = 0.06$ (see Table 2).

Psychophysiological activity. It should be noted that we had missing data for ETCO_2 ($n = 23$; 7 HD, 5 ANX, 11 HC) due to equipment failure. For ETCO_2 , there were no main effects of group, $F(2, 64) = 1.47$, $p = .237$, $\eta^2_p = 0.04$ or task, $F(1, 64) = 1.62$, $p = .208$, $\eta^2_p = 0.03$ and no interaction, $F(2, 64) = 1.56$, $p = .219$, $\eta^2_p = 0.05$. For HRV, there were no main effects of group, $F(2, 82) = 1.15$, $p = .320$, $\eta^2_p = 0.03$ or task, $F(1, 82) = 0.24$, $p = .625$, $\eta^2_p = 0.00$ and no interaction, $F(2, 82) = 0.57$, $p = .566$, $\eta^2_p = 0.01$. For HR, there were no main effects of group, $F(2, 82) = 1.61$, $p = .206$, $\eta^2_p = 0.04$ or task, $F(1, 82) = 1.26$, $p = .265$, $\eta^2_p = 0.02$ and no interaction, $F(2, 82) = 0.15$, $p = .863$, $\eta^2_p = 0.00$.

We also had missing EDA data for 18 participants (4 HD, 8 ANX, 6 HC) due to quality control issues. For SCL, there were no main effects of group, $F(2, 69) = 1.06$, $p = .351$, $\eta^2_p = 0.03$ or task, $F(1, 69) = 2.19$, $p = .143$, $\eta^2_p = 0.03$ and no interaction, $F(2, 69) = 0.58$, $p = .562$, $\eta^2_p = 0.02$. Finally, for SCRs, there were no main effects of group, $F(2, 69) = 1.44$, $p = .244$, $\eta^2_p = 0.04$ or task, $F(1, 69) = 1.62$, $p = .207$, $\eta^2_p = 0.02$ and no interaction, $F(2, 69) = 0.43$, $p = .650$, $\eta^2_p = 0.01$.

Contrary to hypotheses, these findings indicate no differences in psychophysiological activity among the groups or between the two tasks. See Table 2 for means and standard deviations across groups.

Prediction of Hoarding Severity

The ERN during the simulated discarding task did not predict SI-R total ($\beta = -0.07$, $p = .559$) or subscale (Clutter: $\beta = -0.06$, $p = .573$; Difficulty Discarding, $\beta = -0.03$, $p = .794$; Acquiring, $\beta = -0.10$, $p = .379$) scores, controlling for age.

Discussion

The aim of this study was to compare CNS activity, measured with ERN and alpha asymmetry, and PNS activity, measured by HRV, HR, ETCO₂, SCL, and SCR, during simulated discarding decisions and emotionally neutral decisions in individuals with HD, anxious control participants, and healthy control participants. Contrary to hypotheses, there were no significant group differences on any CNS or PNS measures for neutral or discarding decisions. The ERN during the simulated discarding task was not associated with hoarding symptoms. We offer some potential explanations for these null findings below.

As described above, we had initially intended to use a simulated discarding task that had been used in prior research on the ERN (Baldwin, Whitford, & Grisham, 2016). However, we had to modify the original task to increase its difficulty and obtain more errors to reliably measure the ERN, and we may have unintentionally ended up with more of a visual detection task (participants had to distinguish between newspapers that did and did not have pictures on them) rather than a discarding-related decision-making task. Prior studies that have found exaggerated activity in frontal brain regions and excessive psychophysiological activation during discarding decisions have used more ecologically valid tasks that likely were more emotionally salient for those with HD, including sorting and discarding personal possessions or imagined personal possessions (Levy, Nett, & Tolin, 2019; Stevens et al., 2020; Tolin et al., 2012). On the other hand, the task itself would not explain why the neutral (non-discarding) task also showed no group differences for CNS or PNS activity. Prior studies have found decreased activity in frontal regions during neutral (non-discarding) error processing tasks (Mathews et al., 2016; Sunol et al., 2019) and during tasks involving discarding others' possessions (Tolin et al., 2012). By contrast, Hough et al. (2016) reported greater activity in frontal regions during error processing, making it challenging to draw conclusions about CNS processes during decision-making in HD.

Alternatively, it is possible that our use of EEG hampered our ability to detect HD-related abnormalities. As described above, the most reliable evidence of exaggerated CNS activity during discarding decisions comes from fMRI research (Stevens et al., 2020; Tolin et al., 2012). The major advantage of EEG relative to fMRI is the ability to assess moment-to-moment changes in brain activity, which is not possible in fMRI due to the delayed BOLD signal. However, the ERN occurs at a very specific time following commission of an error [approximately 50 milliseconds after the error; for a review, see Olvet and Hajcak (2008)], so the tasks must be timed exactly to capture the effect. Discarding tasks involving real possessions, by nature, cannot be timed this precisely, making it challenging to design an ecologically valid discarding task that is also accurate for measuring the ERN.

We also did not find evidence of greater right vs. left alpha asymmetry during a baseline resting period in HD relative to the anxious and healthy control groups. To our knowledge, this study is the first to assess alpha asymmetry in individuals with HD. Prior research has shown that depression, which is commonly comorbid with HD, is characterized by right lateralized alpha asymmetry (Coan & Allen, 2004; Kemp et al., 2010), although it should be noted that a meta-analysis did not find alpha asymmetry differences between patients with major depressive disorder and healthy controls (van der Vinne et al., 2017). We were surprised by this finding, particularly because patients with HD commonly engage in avoidance behaviors (particularly discarding their possessions) and they experience social impairment often characterized by withdrawal from significant others. Alpha asymmetry has previously been linked to avoidance/withdrawal motivation (Coan, Allen, & Harmon-Jones, 2001). On the other hand, other mental health disorders characterized by avoidance that are often comorbid with HD, including anxiety-related disorders, have not consistently shown significantly right lateralized alpha asymmetry (Harrewijn, Van der Molen, & Westenberg, 2016; Kemp et al., 2010; Smith, Zambrano-Vazquez, & Allen, 2016). Based on the results of the current study, alpha asymmetry may not be a fruitful biomarker for future study in HD.

Future investigations of CNS and PNS responses to decision-making in HD may require more ecologically valid discarding tasks. Although this may be challenging due to the barriers we described above, a potential avenue for future research is the use of virtual reality technology, which was tested and showed promise in terms of treatment acceptability and enhancing motivation for change in reducing clutter (Chasson et al., 2020). In this work, participants were immersed in a virtual reality environment that depicted rooms in their own homes. It is possible that a virtual reality environment would preserve the ecological validity of a

discarding task but also allow the individual discarding decisions to be timed accurately enough to measure the ERN.

In addition to the methodological challenges described above, the current study had other limitations. First, the study was conducted during the COVID-19 pandemic, when recruitment for in-laboratory studies was particularly difficult. Because we were attempting to recruit individuals with HD, who are typically older, we suspect that many prospective participants declined the study due to discomfort about attending an in-person appointment. We also faced unexpected data loss due to equipment malfunctions, which further reduced our sample size and statistical power. It should be noted that the effect sizes we obtained in the current study were so small (ranging from $\eta^2_p = 0.00-0.06$) that it would have taken very large samples to detect these effects; we thus do not have reason to suspect that a larger sample would have greatly changed the results of the current study. Furthermore, our *a priori* power analysis indicated that our sample was large enough to detect at least a medium effect (see above). Our sample was also limited in terms of racial diversity. Second, despite our efforts to match the control groups to the HD group for age and sex, we ended up with age differences and had to control for age in the study analyses. To ensure that covarying age did not undermine our statistical power, we re-ran the study analyses excluding the covariate and found similar results for the ERN and psychophysiological activity. Nevertheless, matching for age across comparison groups is an important consideration for EEG research, given normative changes in neural activity that are associated with aging (Daselaar et al., 2015; Meyer, 2017; Raz et al., 2005; Rodrigue & Raz, 2004; Walhovd et al., 2011).

Further clarification of the neurobiology of HD is hoped to point to novel biological mechanisms that could be targeted in intervention development. As an example, a recent study in undergraduate students found that a single-session cognitive-behavioral intervention focused on reducing error sensitivity decreased the ERN, particularly for those with the highest baseline ERN (Meyer et al., 2020). It will also be important to further test the proposed neurobiological model of HD (Tolin, 2023). One particular area that remains to be studied pertains to the hypoactivity observed at rest (Saxena et al., 2004) and in neutral (non-discarding) tasks (Mathews et al., 2016; Sunol et al., 2019) among individuals with HD. It is unclear whether this hypoactivity is a critical or causal mechanism of HD or simply a side effect of HD symptoms. We look forward to future work that addresses these questions.

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Conflict-of-Interest Statement

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