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Original Article

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Raw scores on subjective sleepiness, fatigue, and vigor metrics consistently define resilience and vulnerability to sleep loss

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Abstract

Study Objectives: Although trait-like individual differences in subjective responses to sleep restriction (SR) and total sleep deprivation (TSD) exist, reliable characterizations remain elusive. We comprehensively compared multiple methods for defining resilience and vulnerability by subjective metrics.

Methods: A total of 41 adults participated in a 13-day experiment: 2 baseline, 5 SR, 4 recovery, and one 36 h TSD night. The Karolinska Sleepiness Scale (KSS) and the Profile of Mood States Fatigue (POMS-F) and Vigor (POMS-V) were administered every 2 h. Three approaches (Raw Score [average SR score], Change from Baseline [average SR minus average baseline score], and Variance [intraindividual SR score variance]), and six thresholds (±1 standard deviation, and the highest/lowest scoring 12.5%, 20%, 25%, 33%, and 50%) categorized Resilient/Vulnerable groups. Kendall's tau-b correlations compared the group categorization's concordance within and between KSS, POMS-F, and POMS-V scores. Bias-corrected and accelerated bootstrapped *t*-tests compared group scores.

Results: There were significant correlations between all approaches at all thresholds for POMS-F, between Raw Score and Change from Baseline approaches for KSS, and between Raw Score and Variance approaches for POMS-V. All Resilient groups defined by the Raw Score approach had significantly better scores throughout the study, notably including during baseline and recovery, whereas the two other approaches differed by measure, threshold, or day. Between-measure correlations varied in strength by measure, approach, or threshold.

Conclusions: Only the Raw Score approach consistently distinguished Resilient/Vulnerable groups at baseline, during sleep loss, and during recovery––we recommend this approach as an effective method for subjective resilience/vulnerability categorization. All approaches created comparable categorizations for fatigue, some were comparable for sleepiness, and none were comparable for vigor. Fatigue and vigor captured resilience/vulnerability similarly to sleepiness but not each other.

Statement of Significance

Trait-like individual differences in subjective responses to sleep loss exist, though how to reliably categorize individuals as resilient or vulnerable remains unknown. A systematic comparison of various categorization methods revealed a lack of synonymy among the approaches, thresholds, and subjective metrics examined (Karolinska Sleepiness Scale, Profile of Mood States Fatigue and Vigor scores). Notably, only average raw scores during SR consistently distinguished resilient and vulnerable groups throughout the study, including at baseline and an extended recovery period, regardless of the threshold used to divide these groups––thus, we recommend raw scores as a useful categorization method. Our findings evince the importance of identifying biomarkers and countermeasures for different subjective components of vulnerability to sleep deprivation, since low sleepiness, low fatigue, and high vigor levels are crucial to maintain in applied settings.

Key words: individual differences; sleep deprivation; Karolinska Sleepiness Scale; Profile of Mood States; recovery; resilient; vulnerable; sleepiness; fatigue; vigor

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Introduction

Adequate sleep is essential for the maintenance of waking cognitive performance and subjective states [1, 2]. The well-established neurobehavioral consequences resulting from sleep deprivation include decrements in subjective sleepiness and fatigue, mood, and attention [3–6]. Differential responses to both chronic sleep restriction (SR) and total sleep deprivation (TSD), whereby individuals are either neurobehaviorally resilient or vulnerable to sleep loss, are stable and trait-like [7–15], yet the methods for reliably determining such differential resilience and vulnerability remain unclear and require further investigation.

Numerous approaches have been utilized to categorize individuals as resilient or vulnerable to the effects of sleep deprivation. While some studies have used raw performance or self-rated scores on neurobehavioral tasks during sleep loss to create such categorizations [11, 16–19], others have used difference scores that account for baseline performance [20–26]. Notably, intraindividual variance in neurobehavioral performance has been posited as another potential factor underlying individual differences, as it may indicate cognitive vulnerability [27–30] and encompass time-of-day variation [5, 31–36]; however, this approach has not yet been explicitly studied for determining vulnerability to sleep deprivation.

The threshold used to create resilient and vulnerable groups is another important factor. Previous studies have classified individuals as resilient or vulnerable using various thresholds, with a median split (50% threshold) [16–18, 20, 23, 24, 37–41] or a tertile split (33% threshold) [11, 22, 26, 42] on neurobehavioral metrics as the most common divisions. Resilience and vulnerability to sleep loss have also been determined using a quartile split (25% threshold) [19, 43] or other numeric divisions of neurobehavioral performance [21, 44]. Classifying individuals as resilient or vulnerable using ±1 standard deviation (*SD*) of neurobehavioral performance as a threshold has not yet been investigated. Notably, the aforementioned approaches and thresholds have not been explicitly compared with each other in relation to the effects of sleep loss on subjective measures, and thus it remains unknown whether the various methods for classification are synonymous.

It is well established that sleep deprivation produces increased feelings of sleepiness and fatigue, and decreased vigor [6, 45–49], and that individual differences related to such subjective decrements are stable and robust across independent, repeated bouts of sleep loss [9, 12–14]. Previous findings have also detected differences in the duration of recovery sleep required for sleepiness, fatigue, and vigor levels to return to baseline following sleep deprivation [45, 50, 51], although further research on recovery profiles of subjective states is needed. Taken together, the aforementioned findings suggest that a differential sensitivity to sleep deprivation and subsequent recovery exists between subjective measures. Furthermore, measures of subjective states are particularly useful in applied settings, as they rapidly and reliably capture factors related to performance decrements resulting from sleep loss [52–57] or sleep inertia upon waking [58, 59]. Thus, systematic examination of the relationship between subjective states, both during sleep-deprived and recovery periods, in individuals who are resilient and vulnerable to sleep loss is needed.

The current study sought to establish whether there is consistency among three different approaches and six discrete thresholds, some which have thus far not been investigated, to identify individuals who are resilient or vulnerable to subjective sleepiness, fatigue, and vigor during sleep loss. We hypothesized the following: (1) resilient and vulnerable categorizations by the three approaches would be similar to each other within each threshold for each measure; (2) for all approaches and at all thresholds, scores would reflect less sleepiness, less fatigue, and more vigor in resilient individuals than in vulnerable individuals on all SR days and during TSD; and (3) resilient and vulnerable categorizations for each measure would be similar to each other.

Methods

Participants

A total of 41 healthy adults (ages 21–49; mean ± *SD*, 33.9 ± 8.9 years; 18 females; 31 African Americans) were recruited for participation in response to advertisements. Reported habitual nightly sleep durations ranged between 6.5 and 8.5 h, with habitual bedtimes between 2200 and 0000 h, and habitual awakenings between 0600 and 0930 h; reported times were confirmed via wrist actigraphy for 1 week prior to study entry (sleep duration, mean ± *SD*, 8.0 ± 0.5 h; sleep midpoint, mean ± *SD*, 3:38 ± 0.8 h; sleep onset, mean ± *SD*, 23:33 ± 0.9 h; sleep offset, mean ± *SD*, 7:39 ± 0.8 h) [14]. The Morningness–Eveningness Composite Scale [60] was used to determine chronotype, with extreme morning and extreme evening types excluded (Morningness–Eveningness Composite Scale score, mean ± *SD*, 41.5 ± 5.8) [14]. For 7 days prior to the study, participant use of caffeine, alcohol, medications (except oral contraceptive use in some females), and tobacco were not allowed, as confirmed by urine and blood screenings. Participant bedtimes and waketimes were monitored at home via actigraphy, sleep–wake diaries, and time-stamped call-ins during the 7–14 days before the in-laboratory phase. See Yamazaki et al. [45] for further information on participant recruitment, inclusion and exclusion criteria, and sample characteristics.

The protocol was approved by the University of Pennsylvania's Institutional Review Board. All participants provided written informed consent in accordance with the Declaration of Helsinki and were compensated for their participation.

Procedures

Participants engaged in a 13-day laboratory study in which they were monitored continuously and received checks of vital signs and symptoms by nurses each day (with a physician on call). The study consisted of two nights of baseline sleep of 10 h (baseline day 1 [B1], 2200–0800 h) and 12 h (baseline day 2 [B2], 2200–1000 h) time in bed (TIB), respectively, followed by five consecutive nights of 4 h TIB per night (sleep restriction days 1–5 [SR1–SR5], 0400–0800 h), four consecutive nights of 12 h TIB per night (recovery days 1–4 [R1–R4], 2200–1000 h), and 36 h of TSD (0 h TIB, wakefulness from 1000 to 2200 h the following day). Participants were monitored continuously by trained staff throughout the study to ensure adherence to the protocol. Additionally, polysomnography (PSG) was recorded on certain nights including B2. Participants' sufficient habitual sleep duration (average of 8 h) in addition to two baseline nights of 10 and 12 h TIB (B2: mean PSG total sleep time [TST] ± *SD*, 9.46 ± 1.07 h) affirms that they were well rested upon entering SR1.

See Yamazaki et al. [45] for additional details regarding permitted participant activities and the laboratory environment throughout the study. Only participants who underwent the SR condition first in Yamazaki et al. [45] were included in the present study.

Neurobehavioral measures

A precise computer-based neurobehavioral test battery was administered every 2 h during wakefulness on all 13 days of the study. The test battery included the Karolinska Sleepiness Scale (KSS) [61] and the Profile of Mood States Fatigue and Vigor scales (POMS-F and POMS-V) [62]. The KSS is a Likert-scale rated (1 = Extremely alert to 9 = Very sleepy, great effort to keep awake, fighting sleep), self-report measure of sleepiness frequently used in sleep deprivation studies [45, 61, 63]. The POMS is a 65-item, Likert-scale rated, self-report measure that assesses a variety of mood states using specific subscales; the fatigue and vigor subscales are commonly used in sleep deprivation studies [45, 64–66]. KSS score, POMS-F score, and POMS-V score were the outcome measures for this study. B1 served as an adaptation day and thus, these KSS and POMS data were excluded from analyses. Due to protocol scheduling conflicts, KSS and POMS data were missing for the B2 2000 h (for KSS: *N* = 26 participants; POMS-F: *N* = 26 participants; POMS-V: *N* = 26 participants), SR5 0800 h (for KSS: *N* = 22 participants; POMS-F: *N* = 25 participants; POMS-V: *N* = 25 participants), and R1 1000 h (for KSS: *N* = 22 participants; POMS-F: *N* = 25 participants; POMS-V: *N* = 25 participants) test bouts.

Resilient, vulnerable, and intermediate group determination

Resilient (Res), Vulnerable (Vul), and Intermediate (Int) groups were defined by three approaches, as follows: (1) The Raw Score approach that calculated a participant's average score (i.e. mean KSS score, mean POMS-F score, or mean POMS-V score) across the SR1 0800 h to SR5 2000 h test bouts; (2) The Change from Baseline approach that subtracted a participant's mean score across the B2 1000 h to 2000 h test bouts from their own mean score across the SR1 0800 h to SR5 2000 h test bouts; (3) The Variance approach that calculated the intraindividual variance of a participant's scores across the SR1 0800 h to SR5 2000 h test bouts. If scores from single test bouts were missing, averages were calculated using scores from the remaining available test bouts.

The median and interquartile range for average score, average change from baseline, and variance across SR1–SR5 were as follows for each measure: 5.7045 (2.4167) for the KSS score Raw Score approach; 2.5455 (2.6364) for the KSS score Change from Baseline approach; 2.5555 (3.1889) for the KSS score Variance approach; 2.9091 (5.1818) for the POMS-F score Raw Score approach; 2.5682 (4.5576) for the POMS-F score Change from Baseline approach; 7.1010 (14.1929) for the POMS-F score Variance approach; 1.9545 (4.0152) for the POMS-V score Raw Score approach; −3.6056 (4.6364) for the POMS-V score Change from Baseline approach; and 3.9450 (10.5756) for the POMS-V score Variance approach.

Within each approach, Res and Vul groups were defined by six thresholds as follows: (1) ±1 *SD* (Res and Vul groups, each *N* = 0–10 [see Figures 1–9 and Supplementary Table S1 for exact *N* for each measure and approach]); (2) the highest and lowest scoring 12.5% (Res and Vul groups, each *N* = 5); (3) the highest and lowest scoring 20% (Res and Vul groups, each *N* = 8); (4) the highest and lowest scoring 25% (Res and Vul groups, each *N* = 10); (5) the highest and lowest scoring 33% (Res and Vul groups, each *N* = 13); and (6) the highest and lowest scoring 50% (Res group *N* = 20, Vul group *N* = 21). For the Raw Score approach categorization of KSS score and POMS-F score, the −1 *SD* and lowest scoring percentage groups comprised the Res groups (e.g. the lower the KSS or POMS-F score, the more resilient). For the Raw Score approach categorization of POMS-V score, the +1 *SD* and highest scoring percentage groups comprised the Res groups (e.g. the higher the POMS-V score, the more resilient). For the Change from Baseline approach categorization of KSS score and POMS-F score, the −1 *SD* and lowest scoring percentage groups comprised the Res groups (e.g. the lower the change from baseline score, the more resilient). For the Change from Baseline approach categorization of POMS-V score, the +1 *SD* and highest scoring percentage groups comprised the Res groups (e.g. the greater the change from baseline score, the more resilient). For the Variance approach categorization of KSS score, POMS-F score, and POMS-V score, the −1 *SD* and least variable percentage groups comprised the Res groups (e.g. the less variance, the more resilient). At each threshold, the remaining participants who were not categorized into the Res or Vul groups were classified as part of the Int group.

Statistical analysis

Statistical analyses were conducted in the R software environment [67]. BMI, age, and sex composition of the Res and Vul groups were compared for each approach at the 12.5%, 33%, and 50% thresholds for the KSS score, POMS-F score, and POMS-V score groups (comparisons were restricted to three thresholds to limit the number of analyses conducted). A one-way analysis of variance (ANOVA) was used to investigate BMI and age, whereas sex was examined via chi-square tests. Sex was not evaluated between the Res and Vul groups at all 12.5% thresholds or at the 33% threshold for the KSS score Change from Baseline approach since the chi-squared sample size requirements were not met in each cell. Race comparisons were not evaluated between the Res and Vul groups at any threshold since the chi-squared sample size requirements were not met in each cell. Pre-study TST (measured by actigraphy from 7 to 14 days before the study) and B2 TST (measured by PSG) between the Res and Vul groups at the 12.5%, 33%, and 50% thresholds were evaluated via one-way ANOVA.

Kendall's tau-b correlations [68, 69] compared the categorizations of participants (i.e. whether they were in the Res, Vul, or Int group) across the three approaches within each measure at each threshold (e.g. the KSS score Raw Score approach at the 12.5% threshold compared with the KSS score Change from Baseline approach at the 12.5% threshold). Additionally, Kendall's tau-b correlations compared the categorizations of participants between measures and approaches at all thresholds (e.g. KSS score for all approaches and thresholds compared with POMS-F score for all approaches and thresholds). Kendall's tau-b was used for these comparisons due to its nonparametric nature and its ability to analyze ordinal data and to account for the repeating of values (e.g. ties in the ranking of data points); given these criteria, it is considered more accurate relative to Spearman's rank correlation

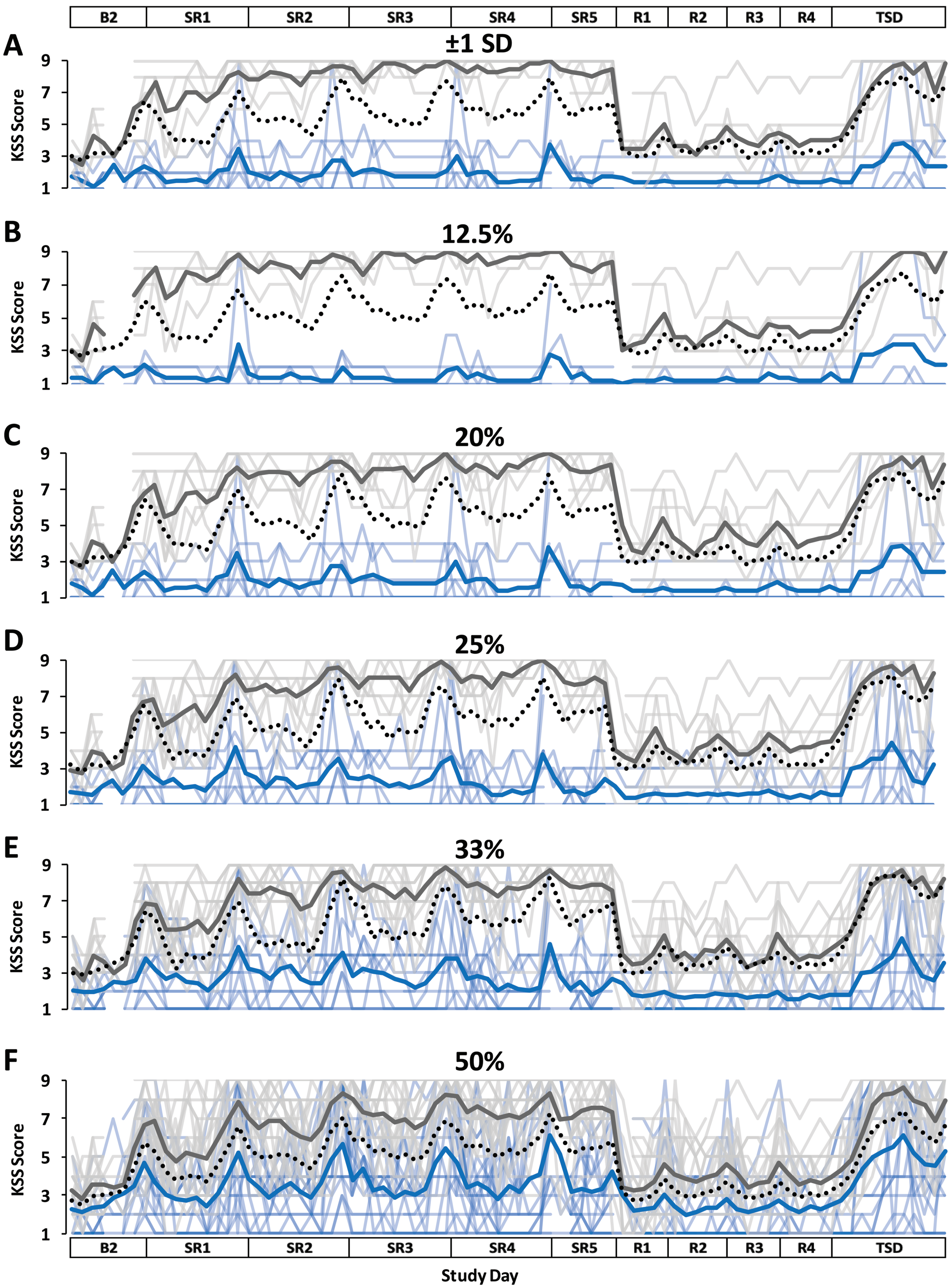

Figure 1. Resilient (Res), Vulnerable (Vul), and Intermediate (Int) group Karolinska Sleepiness Scale (KSS) score profiles across the study using six different thresholds within the Raw Score approach. Res, Vul, and Int groups were determined by averaging KSS scores from all test administrations during sleep restriction days 1–5 (SR1–SR5) (e.g. the lower the KSS score, the more resilient) and using the following six thresholds: (A) ±1 standard deviation (*SD*) (Res *N* = 8; Vul *N* = 6; Int *N* = 27); (B) the highest and lowest scoring 12.5% (Res *N* = 5; Vul *N* = 5; Int *N* = 31); (C) the highest and lowest scoring 20% (Res *N* = 8; Vul *N* = 8; Int *N* = 25); (D) the highest and lowest scoring 25% (Res *N* = 10; Vul *N* = 10; Int *N* = 21); (E) the highest and lowest scoring 33% (Res *N* = 13; Vul *N* = 13; Int *N* = 15); (F) the highest and lowest scoring 50% (Res *N* = 20; Vul *N* = 21; All *N* = 41). See Table 2 for *t*-test comparisons between Res and Vul groups. The top and bottom axis labels depict the study design: baseline day 2 (B2, 1000–2400 h), SR1 (0200 h, 0800–0200 h), SR2–SR4 (0800–0200 h), SR5 (0800–2000 h), recovery days 1–4 (R1–R4, 1000–2000 h), and total sleep deprivation day (TSD, 2200–2000 h). Light blue lines and light gray lines depict individual KSS score profiles for the Res and Vul groups, respectively; the dark blue line and the dark gray line depict averaged KSS score profiles for the Res and Vul groups, respectively. The black dotted line depicts the Int group (except for 50%, for which this line depicts all participants) average KSS score profile. Breaks in the lines indicate missing data.

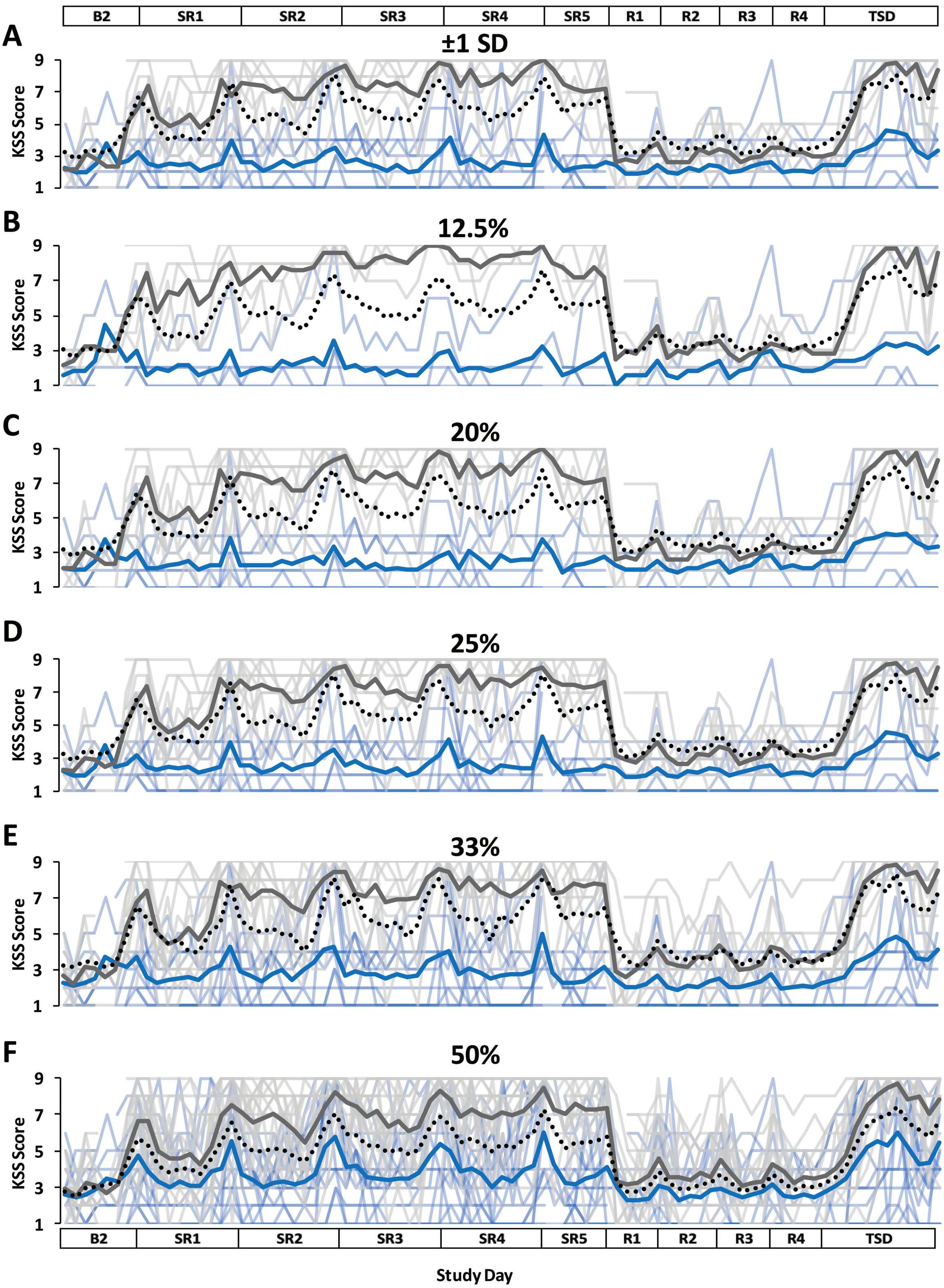

Figure 2. Resilient (Res), Vulnerable (Vul), and Intermediate (Int) group Karolinska Sleepiness Scale (KSS) score profiles across the study using six different thresholds within the Change from Baseline approach. Res, Vul, and Int groups were determined by subtracting each participant's mean KSS score across baseline day 2 (B2) from their mean KSS score across sleep restriction days 1–5 (SR1–SR5) (e.g. the lower the average change from baseline score, the more resilient) and using the following six thresholds: (A) ±1 standard deviation (SD) (Res N = 10; Vul N = 8; Int N = 23); (B) the highest and lowest scoring 12.5% (Res N = 5; Vul N = 5; Int N = 31); (C) the highest and lowest scoring 20% (Res N = 8; Vul N = 8; Int N = 25); (D) the highest and lowest scoring 25% (Res N = 10; Vul N = 10; Int N = 21); (E) the highest and lowest scoring 33% (Res N = 13; Vul N = 13; Int N = 15); (F) the highest and lowest scoring 50% (Res N = 20; Vul N = 21; All N = 41). See Table 2 for *t*-test comparisons between Res and Vul groups. The top and bottom axis labels depict the study design: B2 (1000–2400 h), SR1 (0200 h, 0800–0200 h), SR2–SR4 (0800–0200 h), SR5 (0800–2000 h), recovery days 1–4 (R1–R4, 1000–2000 h), and total sleep deprivation day (TSD, 2200–2000 h). Light blue lines and light gray lines depict individual KSS score profiles for the Res and Vul groups, respectively; the dark blue line and the dark gray line depict the averaged KSS score profiles for the Res and Vul groups, respectively. The black dotted line depicts the Int group (except for 50%, for which this line depicts all participants) average KSS score profile. Breaks in the lines indicate missing data.

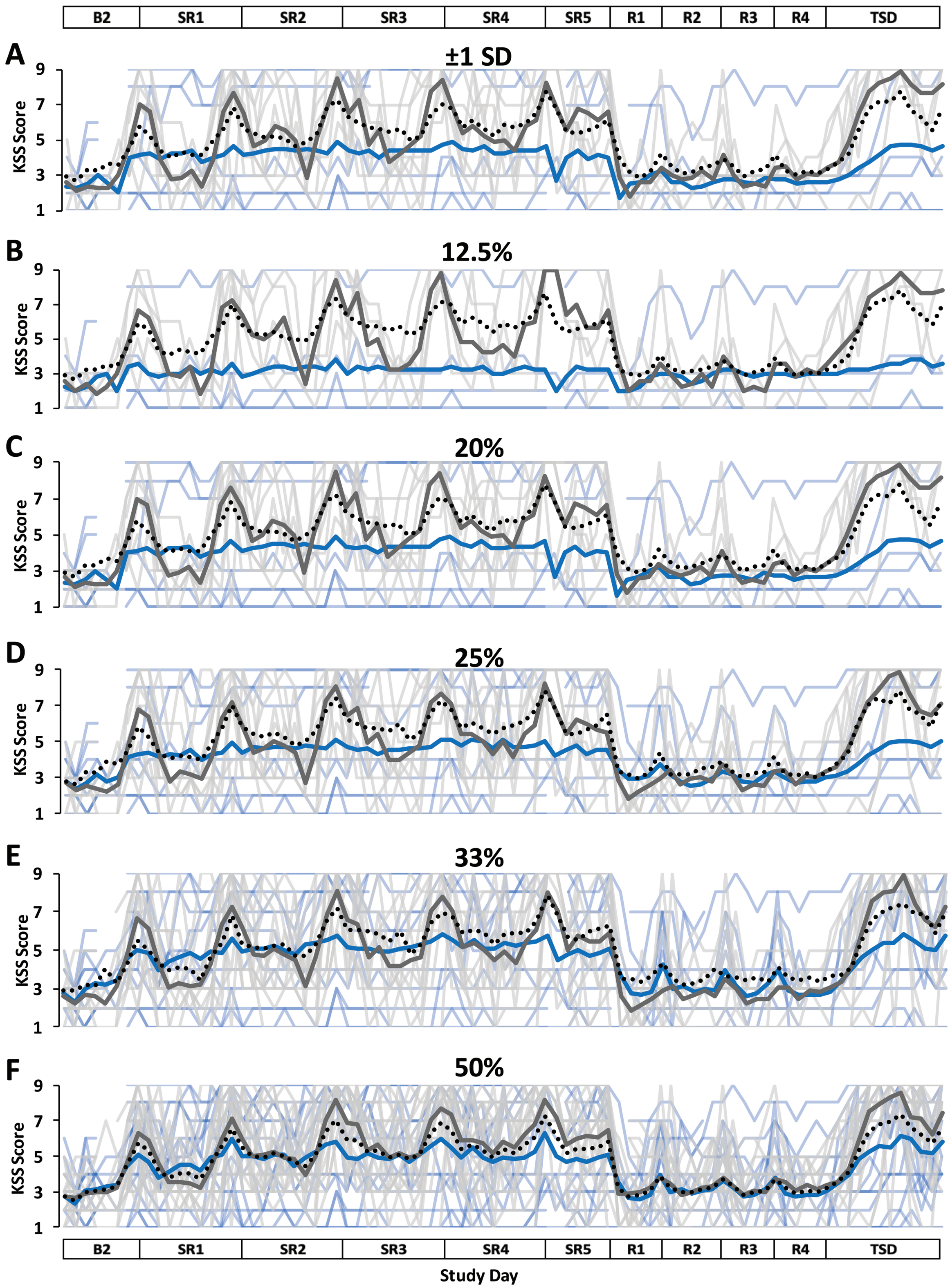

Figure 3. Resilient (Res), Vulnerable (Vul), and Intermediate (Int) group Karolinska Sleepiness Scale (KSS) score profiles across the study using six different thresholds within the Variance approach. Res, Vul, and Int groups were determined by intraindividual variance in KSS scores from all test administrations during sleep restriction days 1–5 (SR1–SR5) (e.g. the less variance, the more resilient) and using the following six thresholds: (A) ±1 standard deviation (*SD*) (Res *N* = 8; Vul *N* = 8; Int *N* = 25); (B) the most and least variable 12.5% (Res *N* = 5; Vul *N* = 5; Int *N* = 31); (C) the most and least variable 20% (Res *N* = 8; Vul *N* = 8; Int *N* = 25); (D) the most and least variable 25% (Res *N* = 10; Vul *N* = 10; Int *N* = 21); (E) the most and least variable 33% (Res *N* = 13; Vul *N* = 13; Int *N* = 15); (F) the most and least variable 50% (Res *N* = 20; Vul *N* = 21; All *N* = 41). See Table 2 for *t*-test comparisons between Res and Vul groups. The top and bottom axis labels depict the study design: baseline day 2 (B2, 1000–2400 h), SR1 (0200 h, 0800–0200 h), SR2–SR4 (0800–0200 h), SR5 (0800–2000 h), recovery days 1–4 (R1–R4, 1000–2000 h), and total sleep deprivation day (TSD, 2200–2000 h). Light blue lines and light gray lines depict individual KSS score profiles for the Res and Vul groups, respectively; the dark blue line and the dark gray line depict the averaged KSS score profiles for the Res and Vul groups, respectively. The black dotted line depicts the Int group (except for 50%, for which this line depicts all participants) average KSS score profile. Breaks in the lines indicate missing data.

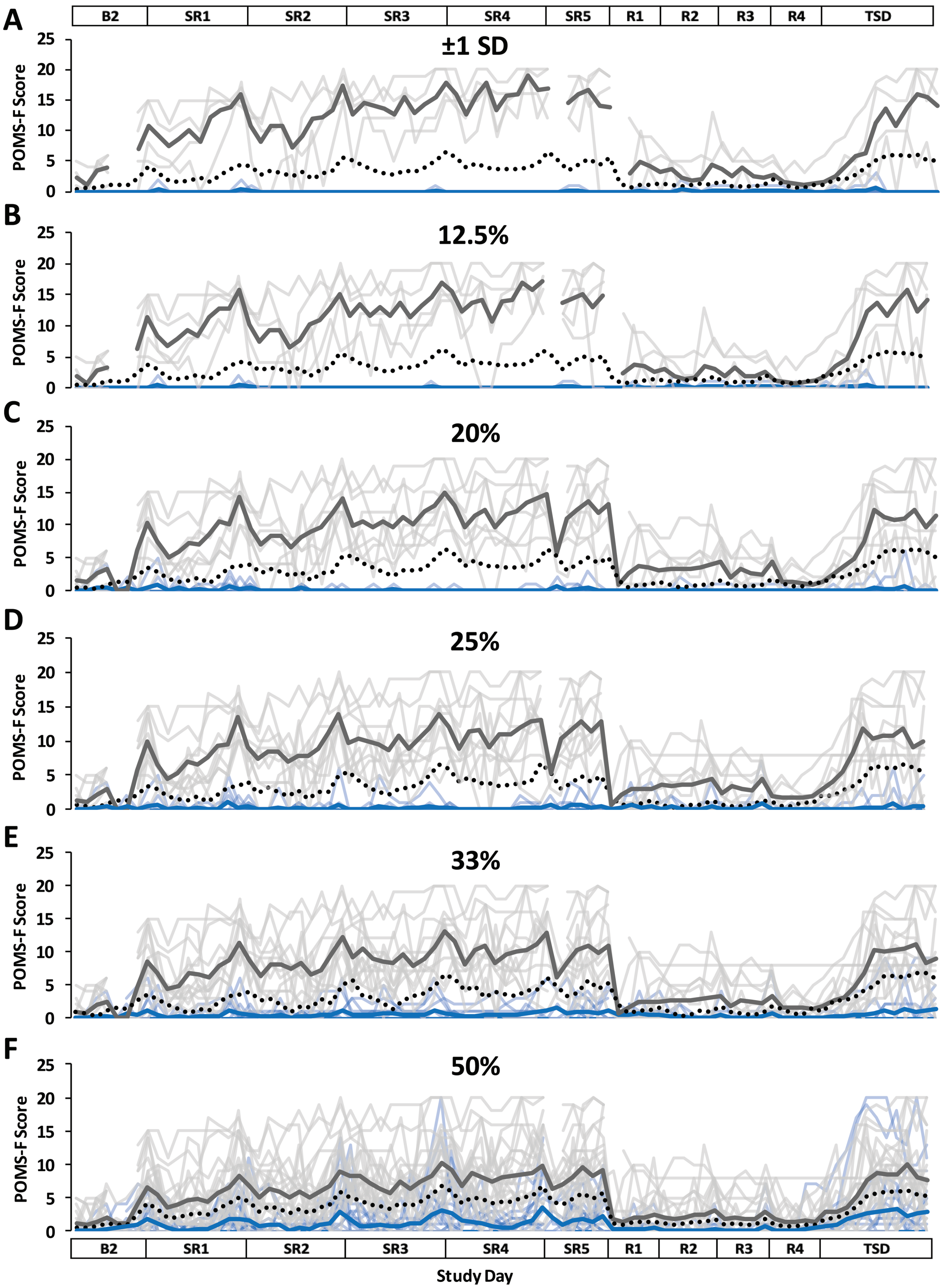

Figure 4. Resilient (Res), Vulnerable (Vul), and Intermediate (Int) group Profile of Mood States Fatigue Scale (POMS-F) score profiles across the study using six different thresholds within the Raw Score approach. Res, Vul, and Int groups were determined by averaging POMS-F scores from all test administrations during sleep restriction days 1–5 (SR1–SR5) (e.g. the lower the POMS-F score, the more resilient) and using the following six thresholds: (A) ±1 standard deviation (*SD*) (Res *N* = 5; Vul *N* = 4; Int *N* = 32); (B) the highest and lowest scoring 12.5% (Res *N* = 5; Vul *N* = 5; Int *N* = 31); (C) the highest and lowest scoring 20% (Res *N* = 8; Vul *N* = 8; Int *N* = 25); (D) the highest and lowest scoring 25% (Res *N* = 10; Vul *N* = 10; Int *N* = 21); (E) the highest and lowest scoring 33% (Res *N* = 13; Vul *N* = 13; Int *N* = 15); (F) the highest and lowest scoring 50% (Res *N* = 20; Vul *N* = 21; All *N* = 41). See Table 2 for *t*-test comparisons between Res and Vul groups. The top and bottom axis labels depict the study design: baseline day 2 (B2, 1000–2400 h), SR1 (0200 h, 0800–0200 h), SR2–SR4 (0800–0200 h), SR5 (0800–2000 h), recovery days 1–4 (R1–R4, 1000–2000 h), and total sleep deprivation day (TSD, 2200–2000 h). Light blue lines and light gray lines depict individual POMS-F score profiles for the Res and Vul groups, respectively; the dark blue line and the dark gray line depict the averaged POMS-F score profiles for the Res and Vul groups, respectively. The black dotted line depicts the Int group (except for 50%, for which this line depicts all participants) average POMS-F score profile. Breaks in the lines indicate missing data.

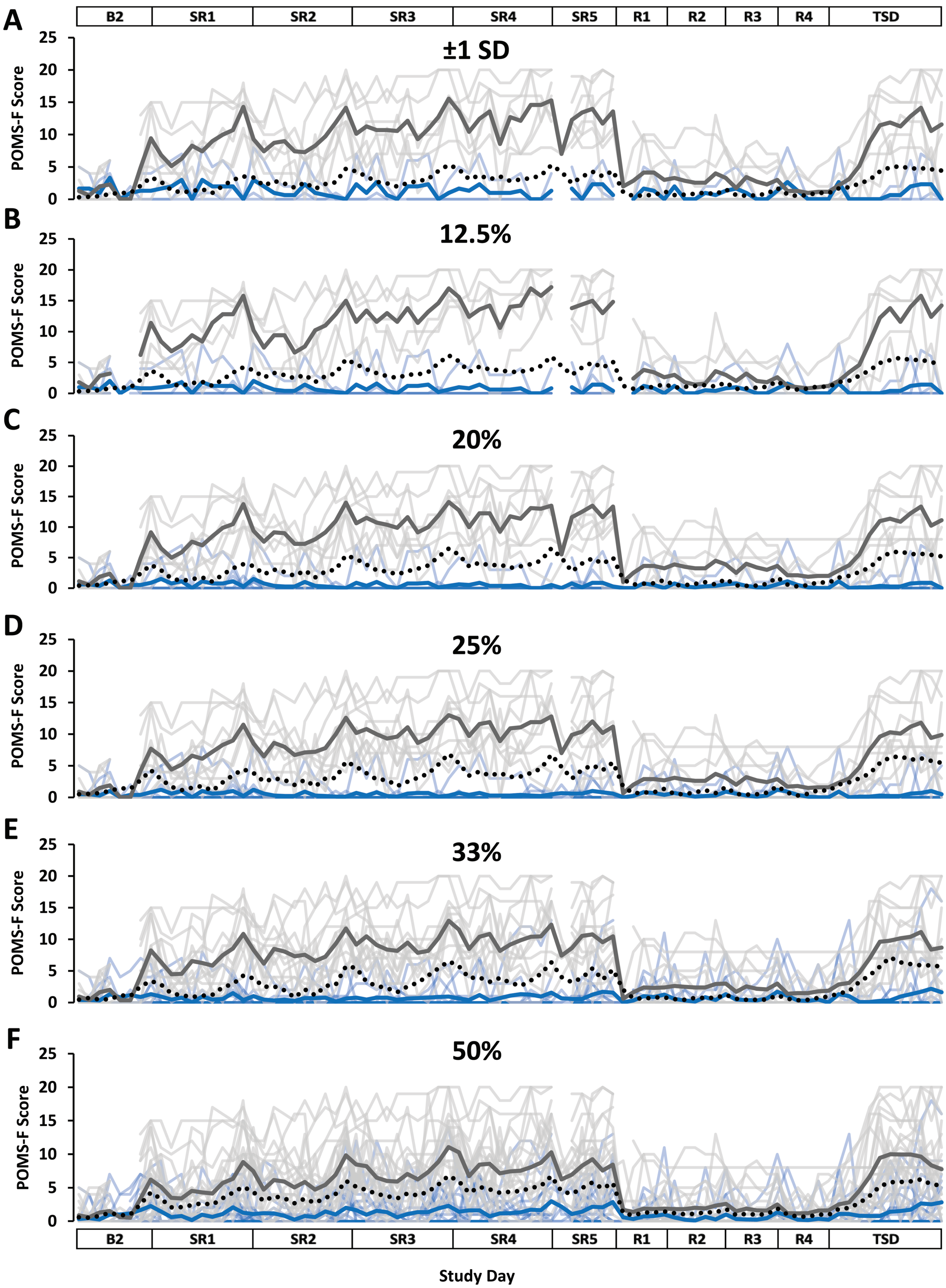

Figure 5. Resilient (Res), Vulnerable (Vul), and Intermediate (Int) group Profile of Mood States Fatigue Scale (POMS-F) score profiles across the study using six different thresholds within the Change from Baseline approach. Res, Vul, and Int groups were determined by subtracting each participant's mean POMS-F score across baseline day 2 (B2) from their mean POMS-F score across sleep restriction days 1–5 (SR1–SR5) (e.g. the lower the average change from baseline score, the more resilient) and using the following six thresholds: (A) ±1 standard deviation (SD) (Res N = 3; Vul N = 7; Int N = 31); (B) the highest and lowest scoring 12.5% (Res N = 5; Vul N = 5; Int N = 31); (C) the highest and lowest scoring 20% (Res N = 8; Vul N = 8; Int N = 25); (D) the highest and lowest scoring 25% (Res N = 10; Vul N = 10; Int N = 21); (E) the highest and lowest scoring 33% (Res N = 13; Vul N = 13; Int N = 15); (F) the highest and lowest scoring 50% (Res N = 20; Vul N = 21; All N = 41). See Table 2 for *t*-test comparisons between Res and Vul groups. The top and bottom axis labels depict the study design: B2 (1000–2400 h), SR1 (0200 h, 0800–0200 h), SR2–SR4 (0800–0200 h), SR5 (0800–2000 h), recovery days 1–4 (R1–R4, 1000–2000 h), and total sleep deprivation day (TSD, 2200–2000 h). Light blue lines and light gray lines depict individual POMS-F score profiles for the Res and Vul groups, respectively; the dark blue line and the dark gray line depict averaged POMS-F score profiles for the Res and Vul groups, respectively. The black dotted line depicts the Int group (except for 50%, for which this line depicts all participants) average POMS-F score profile. Breaks in the lines indicate missing data.

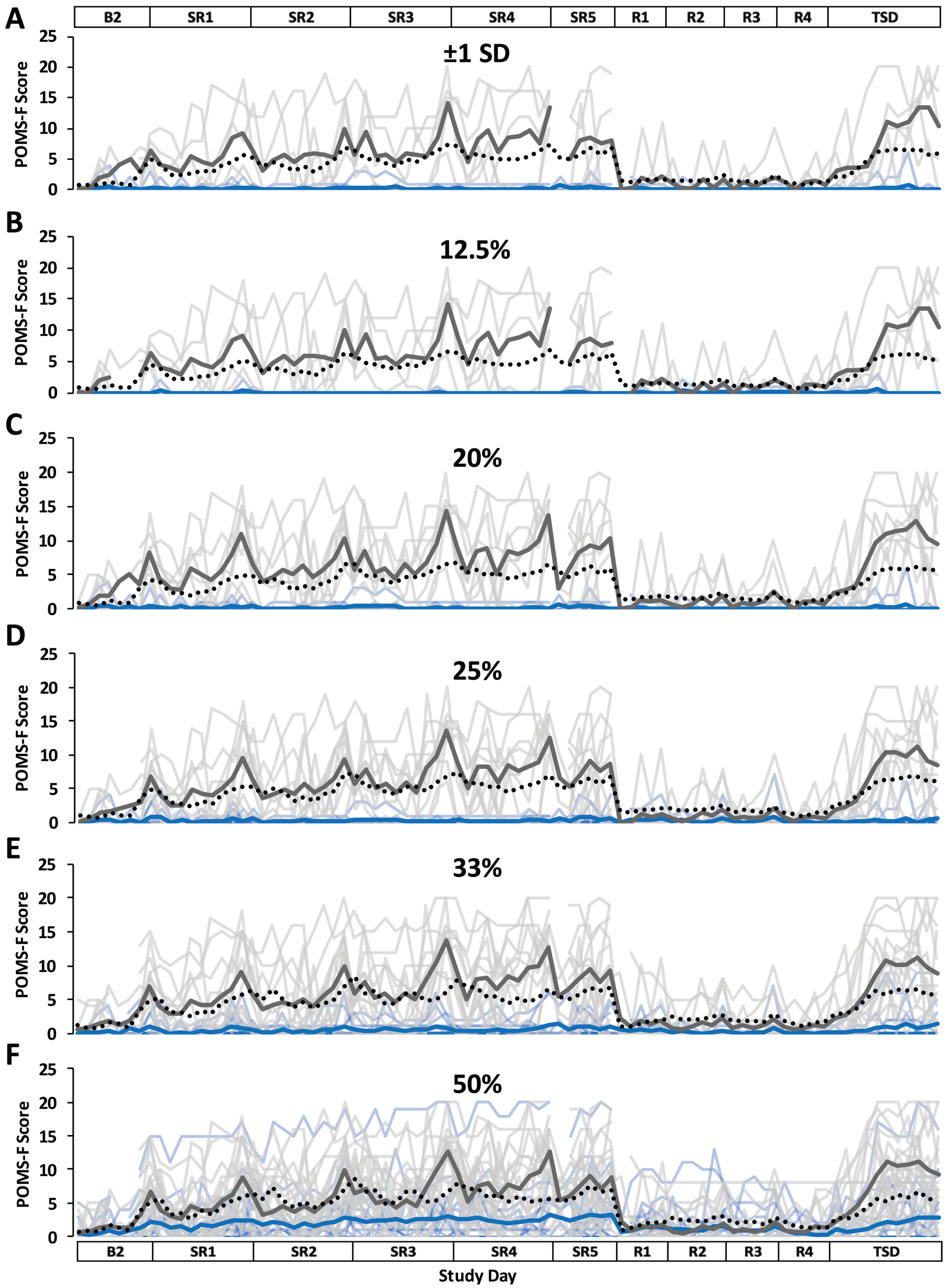

Figure 6. Resilient (Res), Vulnerable (Vul), and Intermediate (Int) group Profile of Mood States Fatigue Scale (POMS-F) score profiles across the study using six different thresholds within the Variance approach. Res, Vul, and Int groups were determined by intraindividual variance in POMS-F scores from all test administrations during sleep restriction days 1–5 (SR1–SR5) (e.g. the less variance, the more resilient) and using the following six thresholds: (A) ±1 standard deviation (SD) (Res N = 8; Vul N = 5; Int N = 28); (B) the most and least variable 12.5% (Res N = 5; Vul N = 5; Int N = 31); (C) the most and least variable 20% (Res N = 8; Vul N = 8; Int N = 25); (D) the most and least variable 25% (Res N = 10; Vul N = 10; Int N = 21); (E) the most and least variable 33% (Res N = 13; Vul N = 13; Int N = 15); (F) the most and least variable 50% (Res N = 20; Vul N = 21; All N = 41). See Table 2 for *t*-test comparisons between Res and Vul groups. The top and bottom axis labels depict the study design: baseline day 2 (B2, 1000–2400 h), SR1 (0200 h, 0800–0200 h), SR2–SR4 (0800–0200 h), SR5 (0800–2000 h), recovery days 1–4 (R1–R4, 1000–2000 h), and total sleep deprivation day (TSD, 2200–2000 h). Light blue lines and light gray lines depict individual POMS-F score profiles for the Res and Vul groups, respectively; the dark blue line and the dark gray line depict the averaged POMS-F score profiles for the Res and Vul groups, respectively. The black dotted line depicts the Int group (except for 50%, for which this line depicts all participants) average POMS-F score profile. Breaks in the lines indicate missing data.

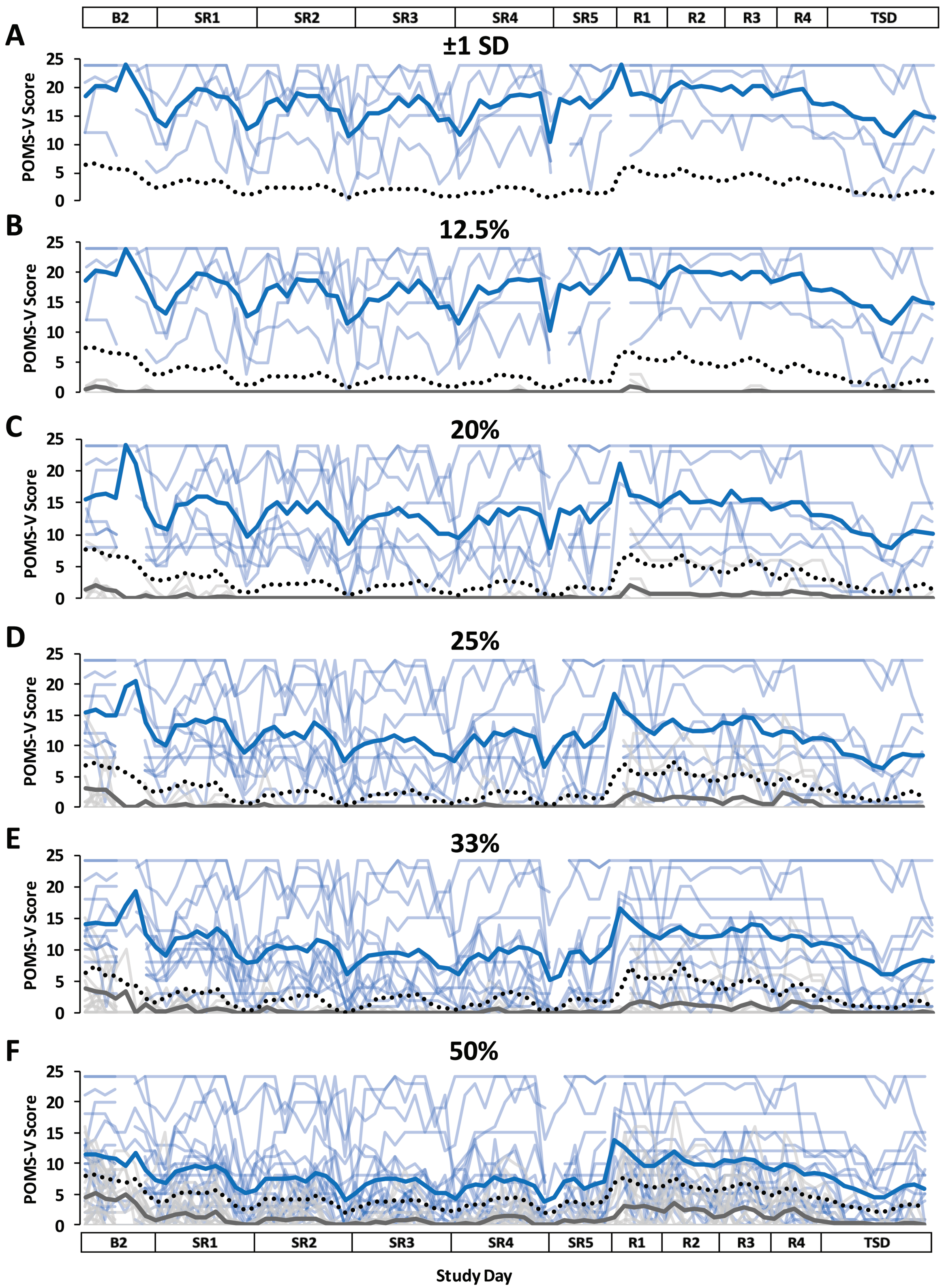

Figure 7. Resilient (Res), Vulnerable (Vul), and Intermediate (Int) group Profile of Mood States Vigor Scale (POMS-V) score profiles across the study using six different thresholds within the Raw Score approach. Res, Vul, and Int groups were determined by averaging POMS-V scores from all test administrations during sleep restriction days 1–5 (SR1–SR5) (e.g. the higher the POMS-V score, the more resilient) and using the following six thresholds: (A) ±1 standard deviation (*SD*) (Res *N* = 5; Vul *N* = 0; Int *N* = 36); (B) the highest and lowest scoring 12.5% (Res *N* = 5; Vul *N* = 5; Int *N* = 31); (C) the highest and lowest scoring 20% (Res *N* = 8; Vul *N* = 8; Int *N* = 25); (D) the highest and lowest scoring 25% (Res *N* = 10; Vul *N* = 10; Int *N* = 21); (E) the highest and lowest scoring 33% (Res *N* = 13; Vul *N* = 13; Int *N* = 15); (F) the highest and lowest scoring 50% (Res *N* = 20; Vul *N* = 21; All *N* = 41). See Table 2 for *t*-test comparisons between Res and Vul groups. The top and bottom axis labels depict the study design: baseline day 2 (B2, 1000–2400 h), SR1 (0200 h, 0800–0200 h), SR2–SR4 (0800–0200 h), SR5 (0800–2000 h), recovery days 1–4 (R1–R4, 1000–2000 h), and total sleep deprivation day (TSD, 2200–2000 h). Light blue lines and light gray lines depict individual POMS-V score profiles for the Res and Vul groups, respectively; the dark blue line and the dark gray line depict the averaged POMS-V score profiles for the Res and Vul groups, respectively. There was no Vul group for the ±1 *SD* threshold due to no participants having a z-score <−1.0. The black dotted line depicts the Int group (except for 50%, for which this line depicts all participants) average POMS-V score profile. Breaks in the lines indicate missing data.

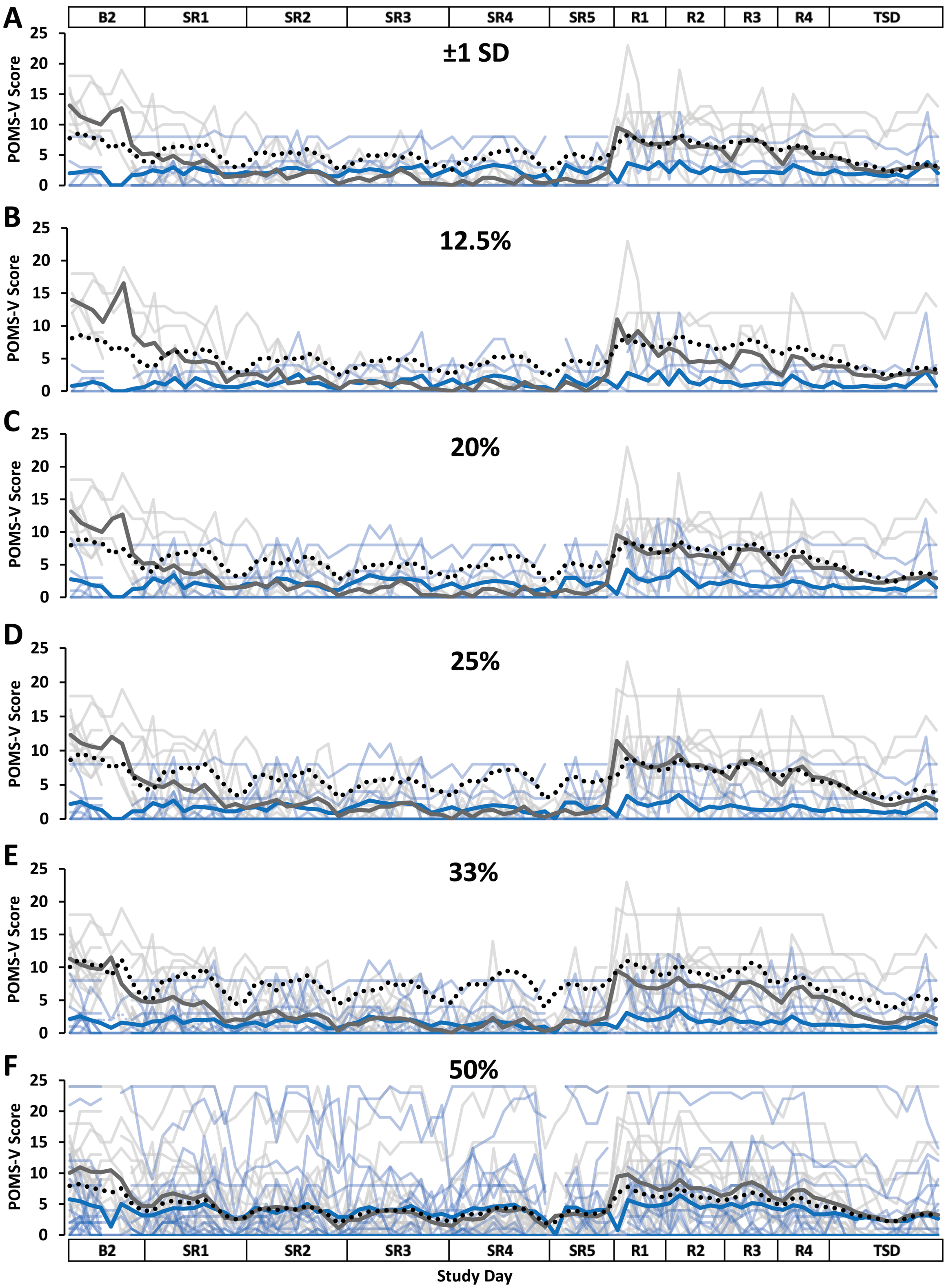

Figure 8. Resilient (Res), Vulnerable (Vul), and Intermediate (Int) group Profile of Mood States Vigor Scale (POMS-V) score profiles across the study using six different thresholds within the Change from Baseline approach. Res, Vul, and Int groups were determined by subtracting each participant's mean POMS-V score across baseline day 2 (B2) from their mean POMS-V score across sleep restriction days 1–5 (SR1–SR5) (e.g. the greater the average change from baseline score, the more resilient) and using the following six thresholds: (A) ±1 standard deviation (SD) (Res N = 6; Vul N = 8; Int N = 27); (B) the highest and lowest scoring 12.5% (Res N = 5; Vul N = 5; Int N = 31); (C) the highest and lowest scoring 20% (Res N = 8; Vul N = 8; Int N = 25); (D) the highest and lowest scoring 25% (Res N = 10; Vul N = 10; Int N = 21); (E) the highest and lowest scoring 33% (Res N = 13; Vul N = 13; Int N = 15); (F) the highest and lowest scoring 50% (Res N = 20; Vul N = 21; All N = 41). See Table 2 for *t*-test comparisons between Res and Vul groups. The top and bottom axis labels depict the study design: B2 (1000–2400 h), SR1 (0200 h, 0800–0200 h), SR2–SR4 (0800–0200 h), SR5 (0800–2000 h), recovery days 1–4 (R1–R4, 1000–2000 h), and total sleep deprivation day (TSD, 2200–2000 h). Light blue lines and light gray lines depict individual POMS-V score profiles for the Res and Vul groups, respectively; the dark blue line and the dark gray line depict the averaged POMS-V score profiles for the Res and Vul groups, respectively. The black dotted line depicts the Int group (except for 50%, for which this line depicts all participants) average POMS-V score profile. Breaks in the lines indicate missing data.

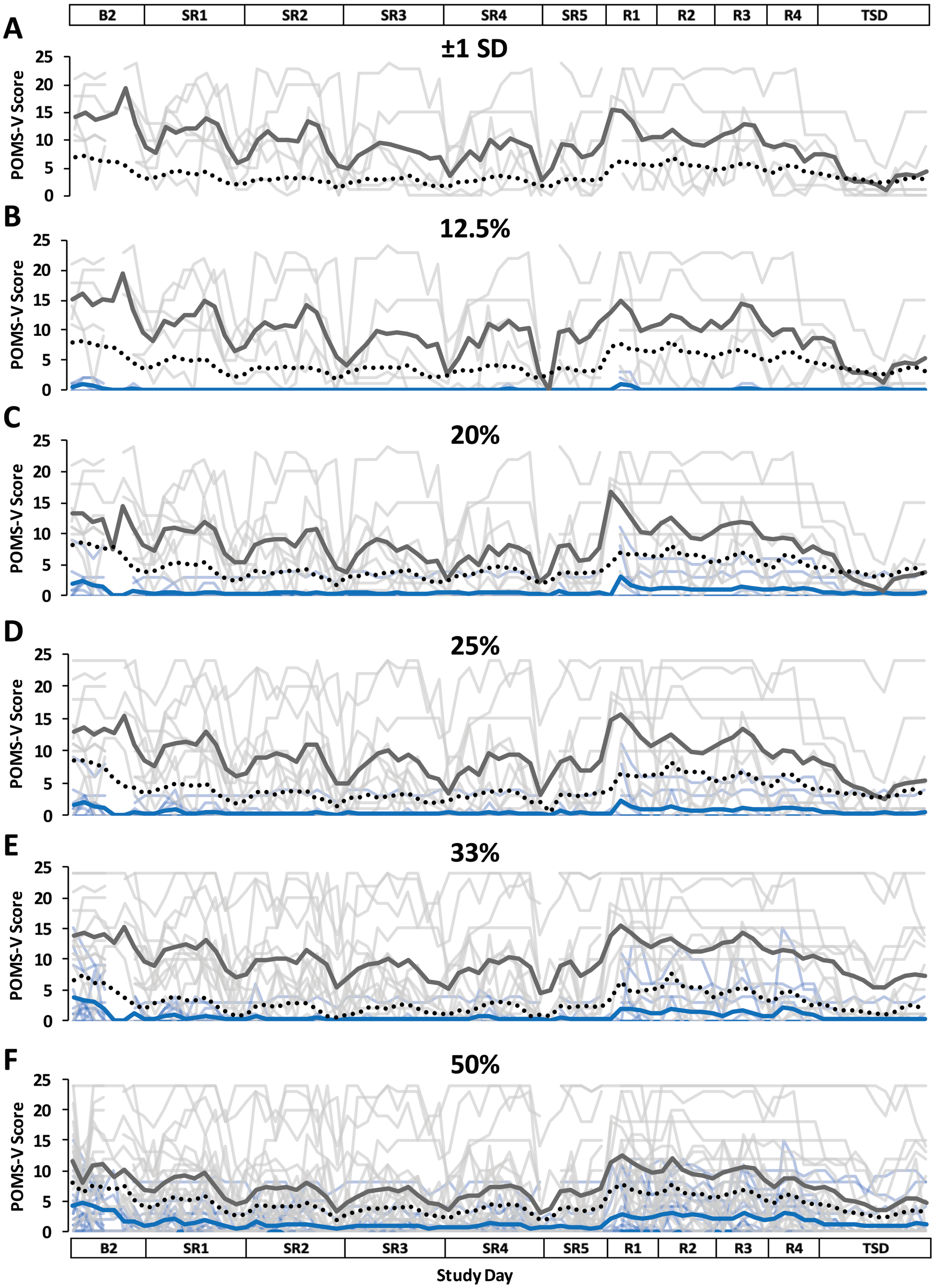

Figure 9. Resilient (Res), Vulnerable (Vul), and Intermediate (Int) group Profile of Mood States Vigor Scale (POMS-V) score profiles across the study using six different thresholds within the Variance approach. Res, Vul, and Int groups were determined by intraindividual variance in POMS-V scores from all test administrations during sleep restriction days 1–5 (SR1–SR5) (e.g. the less variance, the more resilient) and using the following six thresholds: (A) ±1 standard deviation (SD) (Res N = 0; Vul N = 6; Int N = 35); (B) the most and least variable 12.5% (Res N = 5; Vul N = 5; Int N = 31); (C) the most and least variable 20% (Res N = 8; Vul N = 8; Int N = 25); (D) the most and least variable 25% (Res N = 10; Vul N = 10; Int N = 21); (E) the most and least variable 33% (Res N = 13; Vul N = 13; Int N = 15); (F) the most and least variable 50% (Res N = 20; Vul N = 21; All N = 41). See Table 2 for *t*-test comparisons between Res and Vul groups. The top and bottom axis labels depict the study design: baseline day 2 (B2, 1000–2400 h), SR1 (0200 h, 0800–0200 h), SR2–SR4 (0800–0200 h), SR5 (0800–2000 h), recovery days 1–4 (R1–R4, 1000–2000 h), and total sleep deprivation day (TSD, 2200–2000 h). Light blue lines and light gray lines depict individual POMS-V score profiles for the Res and Vul group, respectively; the dark blue line and the dark gray line depict averaged POMS-V score profiles for the Res and Vul groups, respectively. There was no Res group for the ±1 *SD* threshold due to no participants having a z-score <−1.0. The black dotted line depicts the Int group (except for 50%, for which this line depicts all participants) average POMS-V score profile. Breaks in the lines indicate missing data.

for analyzing this data set [69, 70]. Tau-b strength was defined as tau-b = 0.00 to ±0.09: zero; ±0.10 to ±0.39: weak; ±0.40 to ±0.69: moderate; ±0.70 to ±0.99: strong; and ±1.00: perfect [71].

Bias-corrected and accelerated (BCa) bootstrapped *t*-tests with 5000 iterations [72, 73] compared mean KSS score, mean POMS-F score, or mean POMS-V score from the 1000–2000 h test bouts between the Res and Vul groups for each approach and at each threshold on each individual day of the study (e.g. KSS score for the Raw Score approach Res group at the 12.5% threshold compared with KSS score for the Raw Score approach Vul group at the 12.5% threshold on B2). BCa bootstrapped *t*-tests with 5000 iterations also compared average scores of Res and Vul groups across SR1–SR5 (e.g. KSS score for the Raw Score approach Res group at the 12.5% threshold compared with KSS score for the Raw Score approach Vul group at the 12.5% threshold across SR1–SR5).

The false discovery rate (FDR) correction of Benjamini–Hochberg [74] was applied to all bootstrapped *t*-test *p*-values and all within-measure and between-measures Kendall's tau-b correlation *p*-values separately, in accordance with the approach in which the original analyses were performed, to account for multiplicity. Only 9.697% of these *p*-values became nonsignificant when the FDR correction was applied in this manner. Thus, FDR corrected *p*-values are presented for *t*-tests and Kendall's tau-b correlations.

Results

Participant characteristics

The KSS score, POMS-F score, and POMS-V score Res and Vul groups, as defined by any approach or at any threshold, did not significantly differ in BMI, age, or sex at the 12.5%, 33%, or 50% thresholds ($F(1) = 0.000–3.250$; $p = 0.084–0.985$; $\chi^2(1) = 0.000–1.463$; $p = 0.227–1.000$), except for in age by the Variance approach at all thresholds for KSS score, whereby the Res group was significantly older than the Vul group ($F(1) = 6.023–11.050$; $p = 0.011–0.022$; Supplementary Table S2). Additionally, the Res and Vul groups, defined by all three approaches, did not differ significantly in pre-study or B2 TST at the 12.5%, 33%, or 50% thresholds ($F = 0.000–5.147$; $p = 0.053–0.984$), except for KSS score by the Raw Score approach at the 50% threshold ($F(1) = 4.229$; $p = 0.047$; the Res group had a shorter TST at B2 than the Vul group; Supplementary Table S2); for POMS-V score by the Raw Score approach at the 50% threshold ($F(1) = 5.557$; $p = 0.024$; the Res group had a shorter TST at B2 than the Vul group; Supplementary Table S2); and for POMS-V score by the Variance approach at the 12.5% threshold ($F(1) = 10.370$; $p = 0.015$; the Res group had a longer TST at B2 than the Vul group; Supplementary Table S2). Since there were few significant differences detected between Res and Vul groups for age, sex, BMI, or TST characteristics examined for varying measures, approaches, and thresholds, these findings should be interpreted with caution.

Karolinska sleepiness scale

Participants were grouped into Res, Vul, and Int groups by all three approaches (Raw Score, Change from Baseline, and Variance) at all thresholds. For the Raw Score and Change from Baseline approaches at all thresholds, the Res group had significantly lower average KSS scores across SR1–SR5 than the Vul group ($p \leq 0.001–0.005$). However, for the Variance approach, the Res and Vul groups did not significantly differ in average KSS scores across SR1–SR5 at any threshold ($p = 0.353–0.866$). The KSS score profiles of the Res, Vul, and Int groups across the entire study as defined by the Raw Score, Change from Baseline, and Variance approaches at all six thresholds are presented in Figures 1–3, respectively.

Comparison of KSS score resilient and vulnerable approaches Kendall's tau-b correlations comparing the Raw Score and Change from Baseline approach categorizations were significant and tau-b values were moderate to strong at all thresholds ($\tau_b = 0.610–0.730$; $p < 0.001$; Table 1). However, Kendall's tau-b correlations were nonsignificant and tau-b values were zero to weak when comparing the Raw Score and Variance approach categorizations ($\tau_b = –0.075$ to 0.185; $p = 0.322–0.957$; Table 1), and they were nonsignificant and weak when comparing the Change from Baseline and Variance approach categorizations ($\tau_b = 0.143–0.278$; $p = 0.161–0.428$; Table 1).

Comparison of KSS score resilient and vulnerable groups by day As defined by the Raw Score approach, the Res group had significantly lower KSS scores than each respective Vul group at each of the six thresholds and across each study day ($p \leq 0.001–0.012$; Table 2, Figure 1). For the Change from Baseline approach, during all sleep deprivation days (SR1–SR5 and TSD), the Res group had significantly lower KSS scores than the Vul group at all thresholds ($p = 0.001–0.033$; Table 2, Figure 2). During recovery, the Res group had significantly lower KSS scores than the Vul group across R1 (50% threshold), R2 (33% and 50% thresholds), R3 (33% threshold), and R4 (25%, 33%, and 50% thresholds) ($p = 0.002–0.045$; Table 2, Figure 2). All other comparisons within the Change from Baseline approach were nonsignificant ($p = 0.052–0.655$; Table 2, Figure 2). For the Variance approach, the Res group had significantly lower KSS scores than the Vul group only across TSD at the ±1 *SD*, 12.5%, 20%, and 50% thresholds ($p = 0.020–0.034$; Table 2, Figure 3). All other comparisons within the Variance approach were nonsignificant ($p = 0.073–0.997$; Table 2, Figure 3).

Profile of mood states fatigue scale

Participants were grouped into Res, Vul, and Int groups by all three approaches (Raw Score, Change from Baseline, and Variance) at all thresholds. For all three approaches at all thresholds, the Res group had significantly lower average POMS-F scores across SR1–SR5 than the Vul group ($p \leq 0.001–0.012$). The POMS-F score profiles of the Res, Vul, and Int groups across the entire study as defined by the Raw Score, Change from Baseline, and Variance approaches at all six thresholds are presented in Figures 4–6, respectively.

Comparison of POMS-F score resilient and vulnerable approaches Kendall's tau-b correlations comparing the Raw Score and Change from Baseline approach categorizations were significant and tau-b values were moderate to strong at all thresholds ($\tau_b = 0.532–0.853$; $p \leq 0.001$; Table 1). Kendall's tau-b correlations comparing the Raw Score and Variance approach categorizations were significant and tau-b values were moderate to strong at all thresholds ($\tau_b = 0.610–0.750$; $p < 0.001$; Table 1). Kendall's tau-b correlations comparing the Change from Baseline and Variance approach categorizations were also significant at all thresholds and tau-b values were weak to strong (τ_b = 0.366–0.707; $p \le 0.001$–0.014; Table 1).

Comparison of POMS-F score resilient and vulnerable groups by day

As defined by the Raw Score approach, the Res group had significantly lower POMS-F scores than each respective Vul group at all thresholds and across each study day ($p \le 0.001$–0.032; Table 2, Figure 4). For the Change from Baseline approach, during all sleep deprivation days (SR1–SR5 and TSD), the Res group had significantly lower POMS-F scores than the Vul group at all thresholds ($p \le 0.001$–0.011; Table 2, Figure 5). During recovery, the Res group had significantly lower POMS-F scores than the Vul group across R1 (12.5%, 20%, 25%, and 50% thresholds) and R2–R4 (20%, 25%, 33%, and 50% thresholds) (p = 0.002–0.048; Table 2, Figure 5). All other comparisons within the Change from Baseline approach were nonsignificant (p = 0.056–0.873; Table 2, Figure 5). For the Variance approach, the Res group had significantly lower POMS-F scores than the Vul group across SR3, SR4, SR5, R4, and TSD at every threshold ($p \le 0.001$–0.039; Table 2, Figure 6). The Res group as defined by the Variance approach also had significantly lower POMS-F scores than the Vul group across B2, SR1, and SR2 at all thresholds (except for the 50% threshold), R2 (20% and 33% thresholds), and R3 (±1 *SD*, 20%, and 33% thresholds) ($p \le 0.001$–0.046; Table 2, Figure 6). All other comparisons within the Variance approach were nonsignificant (p = 0.050–0.893; Table 2, Figure 6).

Profile of mood states vigor scale

Participants were grouped into Res, Vul, and Int groups by all three approaches (Raw Score, Change from Baseline, and Variance) at all thresholds, except for by the Raw Score approach at the ±1 *SD* threshold, whereby a Vul group was not formed (N = 0), and by the Variance approach at the ±1 *SD* threshold, whereby a Res group was not formed (N = 0), due to the absence of individuals whose average POMS-V score across SR1–SR5 or whose average variance in POMS-V scores across SR1–SR5 was 1 *SD* below the mean, for each approach, respectively. For the Raw Score approach at all thresholds excluding the ±1 *SD* threshold, the Res group had significantly higher average POMS-V scores across SR1–SR5 than the Vul group ($p \le 0.001$–0.002), whereas for the Variance approach at all thresholds excluding the ±1 *SD* threshold, the Res group had significantly lower average POMS-V scores across SR1–SR5 than the Vul group ($p < 0.001$). However, for the Change from Baseline approach, the Res and Vul groups did not significantly differ in average POMS-V scores across SR1–SR5 at any threshold (p = 0.730–0.860). The POMS-V score profiles of the Res, Vul, and Int groups across the entire study as defined by the Raw Score, Change from Baseline, and Variance approaches at all six thresholds are presented in Figures 7–9, respectively.

Comparison of POMS-V score resilient and vulnerable approaches

Kendall's tau-b correlations comparing the Raw Score and Variance approach categorizations were significant and tau-b values were moderate to strong and negative at all thresholds (τ_b = −0.826 to −0.653; $p < 0.001$; Table 1), except for the ±1 *SD* threshold, which was nonsignificant, and the tau-b value was weak (τ_b = −0.267; p = 0.181; Table 1). However, Kendall's tau-b correlations were nonsignificant and tau-b values were zero to weak when comparing the Raw Score and Change from Baseline approach categorizations (τ_b = −0.185 to 0.036; p = 0.316–0.880; Table 1), as well as when comparing the Change from Baseline and Variance approach categorizations (τ_b = 0.077–0.308; p = 0.093–0.690; Table 1).

Table 1. Kendall's tau-b correlations comparing the categorization of participants into the Resilient, Intermediate, and Vulnerable groups for Karolinska Sleepiness Scale (KSS) score, Profile of Mood States Fatigue (POMS-F) score, and Profile of Mood States Vigor (POMS-V) score based on three approaches*

KSS score					POMS-F score					POMS-V score				
Threshold	Approach 1	Approach 2	tau-b	p	Threshold	Approach 1	Approach 2	tau-b	p	Threshold	Approach 1	Approach 2	tau-b	p
±1 SD†	Raw‡	Baseline§	0.730	<0.001	±1 SD	Raw	Baseline	0.532	<0.001	±1 SD	Raw	Baseline	0.036	0.860
	Raw	Variance‖	0.135	0.455		Raw	Variance	0.632	<0.001		Raw	Variance	−0.267	0.181
	Baseline	Variance	0.223	0.243		Baseline	Variance	0.366	0.014		Baseline	Variance	0.077	0.690
12.5%	Raw	Baseline	0.684	<0.001	12.5%	Raw	Baseline	0.785	<0.001	12.5%	Raw	Baseline	−0.185	0.316
	Raw	Variance	0.185	0.322		Raw	Variance	0.678	<0.001		Raw	Variance	−0.678	<0.001
	Baseline	Variance	0.278	0.161		Baseline	Variance	0.481	0.001		Baseline	Variance	0.284	0.131
20%	Raw	Baseline	0.657	<0.001	20%	Raw	Baseline	0.791	<0.001	20%	Raw	Baseline	−0.106	0.559
	Raw	Variance	0.108	0.548		Raw	Variance	0.653	<0.001		Raw	Variance	−0.653	<0.001
	Baseline	Variance	0.226	0.243		Baseline	Variance	0.591	<0.001		Baseline	Variance	0.168	0.316
25%	Raw	Baseline	0.713	<0.001	25%	Raw	Baseline	0.825	<0.001	25%	Raw	Baseline	−0.169	0.316
	Raw	Variance	−0.008	0.957		Raw	Variance	0.652	<0.001		Raw	Variance	−0.713	<0.001
	Baseline	Variance	0.179	0.322		Baseline	Variance	0.652	<0.001		Baseline	Variance	0.308	0.093
33%	Raw	Baseline	0.714	<0.001	33%	Raw	Baseline	0.853	<0.001	33%	Raw	Baseline	−0.170	0.316
	Raw	Variance	−0.075	0.667		Raw	Variance	0.750	<0.001		Raw	Variance	−0.826	<0.001
	Baseline	Variance	0.143	0.428		Baseline	Variance	0.594	<0.001		Baseline	Variance	0.267	0.131
50%	Raw	Baseline	0.610	<0.001	50%	Raw	Baseline	0.707	<0.001	50%	Raw	Baseline	0.024	0.880
	Raw	Variance	0.024	0.932		Raw	Variance	0.610	<0.001		Raw	Variance	−0.660	<0.001
	Baseline	Variance	0.219	0.299		Baseline	Variance	0.707	<0.001		Baseline	Variance	0.219	0.299

Kendall's tau-b correlation coefficients and Benjamini–Hochberg corrected *p*-values are presented.

*Three different approaches (Raw Score, Change from Baseline, and Variance) defined Resilient and Vulnerable groups based on sleep restriction performance within each measure.

†SD = standard deviation.

‡Raw = Raw Score approach.

§Baseline = Change from Baseline approach.

‖Variance = Variance approach.

Table 2. Comparisons of Resilient and Vulnerable group means for Karolinska Sleepiness Scale (KSS) score, Profile of Mood States Fatigue (POMS-F) score, and Profile of Mood States Vigor (POMS-V) score on each study day within each approach*

	KSS score				POMS-F score				POMS-V score			
Study day	Threshold	Raw score *p*-value	Change from Baseline *p*-value	Variance *p*-value	Threshold	Raw score *p*-value	Change from Baseline *p*-value	Variance *p*-value	Threshold	Raw score *p*-value	Change from Baseline *p*-value	Variance *p*-value
B2†	±1 *SD*¶	0.001	0.647	0.754	±1 *SD*	<0.001	0.873	0.035	±1 *SD*	—	0.001	—
	12.5%	0.001	0.436	0.876	12.5%	<0.001	0.323	<0.001	12.5%	0.006	<0.001	<0.001
	20%	0.002	0.655	0.785	20%	0.005	0.288	0.027	20%	<0.001	<0.001	<0.001
	25%	0.002	0.539	0.718	25%	0.001	0.320	0.031	25%	<0.001	<0.001	<0.001
	33%	0.002	0.392	0.577	33%	<0.001	0.213	0.003	33%	<0.001	<0.001	<0.001
	50%	0.002	0.516	0.937	50%	<0.001	0.151	0.245	50%	<0.001	0.023	<0.001
SR1‡	±1 *SD*	0.003	0.001	0.436	±1 *SD*	<0.001	0.011	0.006	±1 *SD*	—	0.433	—
	12.5%	0.002	0.002	0.952	12.5%	<0.001	<0.001	<0.001	12.5%	0.004	0.058	<0.001
	20%	0.002	0.001	0.416	20%	<0.001	<0.001	<0.001	20%	<0.001	0.262	<0.001
	25%	0.001	0.001	0.436	25%	<0.001	<0.001	<0.001	25%	<0.001	0.051	<0.001
	33%	0.001	0.002	0.291	33%	<0.001	<0.001	<0.001	33%	<0.001	0.028	<0.001
	50%	0.001	0.009	0.472	50%	<0.001	<0.001	0.113	50%	<0.001	0.376	<0.001
SR2	±1 *SD*	0.003	0.002	0.840	±1 *SD*	<0.001	<0.001	0.001	±1 *SD*	—	0.720	—
	12.5%	0.003	0.003	0.539	12.5%	<0.001	<0.001	<0.001	12.5%	0.003	0.720	<0.001
	20%	0.002	0.002	0.855	20%	<0.001	<0.001	<0.001	20%	<0.001	0.775	<0.001
	25%	0.002	0.002	0.796	25%	<0.001	<0.001	<0.001	25%	<0.001	0.710	<0.001
	33%	0.002	0.002	0.651	33%	<0.001	<0.001	<0.001	33%	<0.001	0.274	<0.001
	50%	0.001	0.001	0.987	50%	<0.001	<0.001	0.052	50%	<0.001	0.995	<0.001
SR3	±1 *SD*	0.002	0.003	0.769	±1 *SD*	<0.001	<0.001	0.001	±1 *SD*	—	0.469	—
	12.5%	0.003	0.006	0.580	12.5%	<0.001	<0.001	<0.001	12.5%	0.002	0.974	<0.001
	20%	0.003	0.003	0.754	20%	<0.001	<0.001	<0.001	20%	<0.001	0.306	<0.001
	25%	0.002	0.002	0.840	25%	<0.001	<0.001	<0.001	25%	<0.001	0.656	<0.001
	33%	0.001	0.002	0.855	33%	<0.001	<0.001	<0.001	33%	<0.001	0.980	<0.001
	50%	0.001	0.001	0.644	50%	<0.001	<0.001	0.039	50%	<0.001	0.707	<0.001
SR4	±1 *SD*	0.004	0.004	0.725	±1 *SD*	<0.001	<0.001	<0.001	±1 *SD*	—	0.073	—
	12.5%	0.005	0.007	0.554	12.5%	0.003	0.003	<0.001	12.5%	<0.001	0.392	<0.001
	20%	0.003	0.003	0.727	20%	<0.001	<0.001	<0.001	20%	<0.001	0.152	<0.001
	25%	0.002	0.003	0.987	25%	<0.001	<0.001	<0.001	25%	<0.001	0.376	<0.001
	33%	0.003	0.002	0.769	33%	<0.001	<0.001	<0.001	33%	<0.001	0.699	<0.001
	50%	0.002	0.002	0.516	50%	<0.001	<0.001	0.016	50%	<0.001	0.589	<0.001
SR5	±1 *SD*	0.002	0.002	0.222	±1 *SD*	0.006	<0.001	<0.001	±1 *SD*	—	0.216	—
	12.5%	0.001	0.005	0.182	12.5%	0.002	0.002	<0.001	12.5%	0.003	0.718	<0.001
	20%	0.002	0.002	0.196	20%	<0.001	<0.001	<0.001	20%	<0.001	0.230	<0.001
	25%	0.002	0.002	0.459	25%	<0.001	<0.001	<0.001	25%	<0.001	0.469	<0.001
	33%	0.002	0.002	0.684	33%	<0.001	<0.001	<0.001	33%	<0.001	0.874	<0.001
	50%	0.002	0.002	0.216	50%	<0.001	<0.001	0.011	50%	<0.001	0.711	<0.001
R1§	±1 *SD*	<0.001	0.100	0.795	±1 *SD*	0.002	0.056	0.128	±1 *SD*	—	0.071	—
	12.5%	<0.001	0.052	0.840	12.5%	0.003	0.030	0.057	12.5%	0.003	0.096	<0.001
	20%	0.001	0.186	0.794	20%	<0.001	0.002	0.121	20%	<0.001	0.046	<0.001
	25%	0.002	0.056	0.250	25%	0.006	0.026	0.414	25%	<0.001	0.002	<0.001
	33%	0.002	0.057	0.141	33%	0.023	0.116	0.050	33%	<0.001	<0.001	<0.001
	50%	0.012	0.029	0.855	50%	<0.001	0.048	0.893	50%	<0.001	0.148	<0.001
R2	±1 *SD*	<0.001	0.183	0.655	±1 *SD*	0.024	0.092	0.072	±1 *SD*	—	0.093	—
	12.5%	<0.001	0.182	0.950	12.5%	0.026	0.091	0.091	12.5%	0.004	0.131	<0.001
	20%	<0.001	0.240	0.647	20%	<0.001	0.006	0.046	20%	<0.001	0.051	<0.001
	25%	<0.001	0.090	0.860	25%	<0.001	0.013	0.051	25%	<0.001	0.002	<0.001
	33%	0.001	0.003	0.746	33%	<0.001	0.011	0.004	33%	<0.001	0.002	<0.001
	50%	0.001	0.024	0.911	50%	<0.001	0.002	0.745	50%	<0.001	0.330	<0.001
R3	±1 *SD*	<0.001	0.255	0.997	±1 *SD*	0.013	0.121	0.022	±1 *SD*	—	0.062	—
	12.5%	<0.001	0.647	0.776	12.5%	0.013	0.079	0.055	12.5%	0.002	0.045	<0.001
	20%	<0.001	0.436	0.975	20%	<0.001	0.006	0.002	20%	<0.001	0.023	<0.001
	25%	<0.001	0.182	0.785	25%	<0.001	0.016	0.071	25%	<0.001	0.001	<0.001
	33%	<0.001	0.023	0.446	33%	<0.001	0.033	0.010	33%	<0.001	0.001	<0.001
	50%	0.002	0.107	0.975	50%	<0.001	0.007	0.527	50%	<0.001	0.297	<0.001
R4	±1 *SD*	<0.001	0.064	0.727	±1 *SD*	0.016	0.681	0.007	±1 *SD*	—	0.246	—
	12.5%	<0.001	0.306	0.914	12.5%	0.032	0.363	0.022	12.5%	<0.001	0.195	<0.001
	20%	<0.001	0.144	0.712	20%	<0.001	0.033	<0.001	20%	<0.001	0.104	0.003
	25%	<0.001	0.045	0.855	25%	<0.001	0.031	<0.001	25%	<0.001	0.005	<0.001
	33%	0.001	0.002	0.912	33%	<0.001	0.030	<0.001	33%	<0.001	0.004	<0.001
	50%	0.002	0.029	0.515	50%	<0.001	0.004	0.037	50%	<0.001	0.312	<0.001

Table 2. Continued

	KSS score				POMS-F score				POMS-V score			
Study day	Threshold	Raw score *p*-value	Change from Baseline *p*-value	Variance *p*-value	Threshold	Raw score *p*-value	Change from Baseline *p*-value	Variance *p*-value	Threshold	Raw score *p*-value	Change from Baseline *p*-value	Variance *p*-value
TSD‖	±1 *SD*	0.003	0.003	0.021	±1 *SD*	0.004	<0.001	0.006	±1 *SD*	—	0.736	—
	12.5%	0.006	0.033	0.034	12.5%	0.003	0.003	0.006	12.5%	<0.001	0.531	<0.001
	20%	0.003	0.003	0.020	20%	<0.001	<0.001	0.001	20%	<0.001	0.518	0.019
	25%	0.002	0.003	0.073	25%	<0.001	<0.001	0.001	25%	<0.001	0.376	<0.001
	33%	0.001	0.002	0.099	33%	<0.001	<0.001	<0.001	33%	<0.001	0.420	<0.001
	50%	0.002	0.001	0.034	50%	<0.001	<0.001	0.001	50%	<0.001	0.830	0.006

Bias-corrected and accelerated bootstrapped *t*-test *p*-values are presented. The Benjamini–Hochberg correction for multiple comparisons was applied to all *p*-values. Analyses were not conducted for the Raw Score and Variance approaches for POMS-V score at the ±1 *SD* threshold due to the absence of a Vulnerable or Resilient group, respectively.

*Three different approaches (Raw Score, Change from Baseline, and Variance) defined Resilient and Vulnerable groups based on sleep restriction performance within each measure.

†B2 = Baseline day 2.

‡SR = Sleep restriction day.

§R = Recovery day.

‖TSD = Total sleep deprivation day.

¶SD = standard deviation.

Comparison of POMS-V score resilient and vulnerable groups by day As defined by the Raw Score approach, the Res group had significantly higher POMS-V scores than each respective Vul group at all thresholds (excluding the ±1 *SD* threshold) and across each study day ($p \leq 0.001$–0.006; Table 2, Figure 7). For the Change from Baseline approach, the Res group had significantly lower POMS-V scores than the Vul group across B2 at all thresholds, SR1 (33% threshold), R1 (20%, 25%, and 33% thresholds), R2 (25% and 33% thresholds), R3 (12.5%, 20%, 25%, and 33% thresholds), and R4 (25% and 33% thresholds) ($p \leq 0.001$–0.046; Table 2, Figure 8). All other comparisons within the Change from Baseline approach were nonsignificant ($p = 0.051$–0.995; Table 2, Figure 8). As defined by the Variance approach, the Res group had significantly lower POMS-V scores than the Vul group at all thresholds (excluding the ±1 *SD* threshold) and across each study day ($p \leq 0.001$–0.019; Table 2, Figure 9).

Comparison of KSS, POMS-F, and POMS-V score resilient and vulnerable approaches

KSS score versus POMS-F score When compared at the same threshold, Kendall's tau-b correlations were significant for all comparisons between the KSS score Raw Score and POMS-F score Raw Score approaches with moderate tau-b values ($\tau_b = 0.47$–0.62; $p = 0.002$–0.012; Table 3), between the KSS score Raw Score and POMS-F score Change from Baseline approaches with moderate tau-b values ($\tau_b = 0.43$–0.67; $p = 0.002$–0.025; Table 3), and between the KSS score Change from Baseline and POMS-F score Raw Score approaches with weak to moderate tau-b values ($\tau_b = 0.38$–0.61; $p = 0.004$–0.049; Table 3). When compared at the same threshold, Kendall's tau-b correlations were significant at the ±1 *SD*, 12.5%, 20%, and 25% thresholds for comparisons between the KSS score Raw Score and POMS-F score Variance approaches and tau-b values were weak to moderate ($\tau_b = 0.38$–0.46; $p = 0.013$–0.049; Table 3). When compared at the same threshold, Kendall's tau-b correlations were significant at the 25%, 33%, and 50% thresholds for comparisons between the KSS score Change from Baseline and POMS-F score Change from Baseline approaches and tau-b values were moderate ($\tau_b = 0.56$–0.61; $p = 0.004$; Table 3). When compared at the same threshold, Kendall's tau-b correlations were significant at the ±1 *SD* and 50% thresholds for comparisons between the KSS score Change from Baseline and POMS-F score Variance approaches and tau-b values were weak to moderate ($\tau_b = 0.37$–0.41; $p = 0.041$–0.048; Table 3). When compared at the same threshold, Kendall's tau-b correlations were significant at the ±1 *SD*, 20%, and 25% thresholds for comparisons between the KSS score Variance and POMS-F score Variance approaches and tau-b values were weak to moderate ($\tau_b = 0.39$–0.40; $p = 0.027$–0.035; Table 3). All other Kendall's tau-b comparisons between KSS score and POMS-F score approach categorizations when compared at the same threshold were nonsignificant ($\tau_b = -0.08$ to 0.35; $p = 0.055$–0.692; Table 3). Table 3 shows detailed results of tau-b values between KSS score and POMS-F score approach categorizations across all thresholds, whereby bolded tau-b values indicate comparisons at the same threshold.

KSS score versus POMS-V score When compared at the same threshold, Kendall's tau-b correlations were significant at the ±1 *SD*, 20%, 25%, and 33% thresholds for comparisons between the KSS score Raw Score and POMS-V score Raw Score approaches and tau-b values were moderate ($\tau_b = 0.43$–0.59; $p = 0.004$–0.016; Table 3). When compared at the same threshold, Kendall's tau-b correlations were significant at the ±1 *SD* threshold for comparisons between the KSS score Raw Score and POMS-V score Change from Baseline approaches, and between the KSS score Change from Baseline and POMS-V score Raw Score approaches and tau-b values were moderate ($\tau_b = 0.41$; $p = 0.029$–0.034; Table 3). When compared at the same threshold, Kendall's tau-b correlations were significant at the ±1 *SD*, 12.5%, 20%, and 25% thresholds for comparisons between the KSS score Change from Baseline and POMS-V score Change from Baseline approaches and tau-b values were weak to moderate ($\tau_b = 0.38$–0.52; $p = 0.006$–0.049; Table 3). When compared at the same threshold, Kendall's tau-b correlations were significant at the 20%, 25%, and 33% thresholds for comparisons between the KSS score Variance and

Table 3. Kendall's tau-b correlations comparing the categorization of participants into the Resilient (Res), Intermediate (Int), and Vulnerable (Vul) groups as defined by the three approaches† between Karolinska Sleepiness Scale (KSS) score, Profile of Mood States Fatigue (POMS-F) score, and Profile of Mood States Vigor (POMS-V) score

			KSS Score																	
			Raw Score						Change from Baseline						Variance					
		Threshold	±1 SD‡	12.5%	20%	25%	33%	50%	±1 SD	12.5%	20%	25%	33%	50%	±1 SD	12.5%	20%	25%	33%	50%
POMS-F score	Raw Score	±1 SD	0.51*	0.51*	0.48*	0.49*	0.49*	0.46*	0.45*	0.30	0.39*	0.41*	0.42*	0.36	0.16	0.10	0.16	0.13	0.12	0.16
		12.5%	0.57*	0.58*	0.53*	0.54*	0.52*	0.48*	0.50*	0.38*	0.45*	0.46*	0.46*	0.38*	0.14	0.09	0.14	0.12	0.05	0.10
		20%	0.52*	0.38*	0.47*	0.53*	0.55*	0.52*	0.45*	0.30	0.41*	0.41*	0.45*	0.45*	0.28	0.14	0.28	0.24	0.08	0.15
		25%	0.58*	0.40*	0.59*	0.62*	0.62*	0.60*	0.44*	0.33	0.41*	0.46*	0.52*	0.53*	0.35	0.19	0.35	0.31	0.15	0.20
		33%	0.55*	0.41*	0.51*	0.59*	0.54*	0.58*	0.47*	0.41*	0.45*	0.45*	0.53*	0.52*	0.31	0.22	0.31	0.31	0.13	0.17
		50%	0.49*	0.38*	0.45*	0.46*	0.52*	0.51*	0.36	0.29	0.37	0.33	0.46*	0.61*	0.30	0.29	0.30	0.33	0.17	0.32
	Change from Baseline	±1 SD	0.43*	0.30	0.46*	0.55*	0.47*	0.40*	0.30	0.20	0.23	0.27	0.29	0.39*	−0.08	−0.10	−0.08	−0.19	−0.28	−0.19
		12.5%	0.48*	0.48*	0.45*	0.54*	0.46*	0.38*	0.35	0.28	0.29	0.33	0.34	0.38*	0.07	0.09	0.07	−0.07	−0.17	−0.10
		20%	0.45*	0.38*	0.47*	0.53*	0.50*	0.45*	0.39*	0.30	0.35	0.42*	0.40*	0.45*	0.22	0.07	0.22	0.15	0.04	0.08
		25%	0.58*	0.47*	0.59*	0.67*	0.62*	0.53*	0.55*	0.47*	0.53*	0.57*	0.52*	0.53*	0.25	0.19	0.25	0.17	0.06	0.13
		33%	0.55*	0.41*	0.55*	0.62*	0.62*	0.58*	0.52*	0.47*	0.50*	0.52*	0.56*	0.58*	0.31	0.28	0.31	0.23	0.10	0.12
		50%	0.41*	0.29	0.37	0.40*	0.46*	0.51*	0.36	0.38*	0.37	0.33	0.46*	0.61*	0.30	0.19	0.30	0.27	0.17	0.22
	Variance	±1 SD	0.42*	0.34	0.39*	0.40*	0.35	0.31	0.37*	0.18	0.33	0.35	0.30	0.23	0.39*	0.34	0.39*	0.35	0.25	0.21
		12.5%	0.40*	0.38*	0.37	0.32	0.28	0.19	0.35	0.19	0.29	0.32	0.28	0.19	0.37*	0.28	0.37*	0.33	0.28	0.29
		20%	0.44*	0.37*	0.46*	0.46*	0.39*	0.37	0.38*	0.22	0.34	0.35	0.35	0.30	0.40*	0.29	0.40*	0.36*	0.22	0.15
		25%	0.39*	0.33	0.41*	0.42*	0.36*	0.33	0.35	0.27	0.36*	0.32	0.32	0.27	0.46*	0.32	0.46*	0.40*	0.27	0.20
		33%	0.39*	0.28	0.36*	0.40*	0.34	0.29	0.29	0.23	0.31	0.23	0.30	0.29	0.49*	0.40*	0.49*	0.47*	0.31	0.29
		50%	0.25	0.19	0.22	0.27	0.29	0.22	0.28	0.19	0.30	0.27	0.35	0.41*	0.52*	0.48*	0.52*	0.46*	0.35	0.32

			KSS Score																	
			Raw Score						Change from Baseline						Variance					
		Threshold	±1 SD	12.5%	20%	25%	33%	50%	±1 SD	12.5%	20%	25%	33%	50%	±1 SD	12.5%	20%	25%	33%	50%
POMS-V score	Raw Score	±1 SD	0.47*	0.29	0.46*	0.51*	0.44*	0.38	0.41*	0.15	0.23	0.41*	0.44*	0.38	0.11	0.00	0.11	0.00	0.00	0.23
		12.5%	0.40*	0.28	0.53*	0.53*	0.47*	0.38*	0.21	0.09	0.07	0.26	0.34	0.38*	0.00	−0.09	0.00	−0.19	−0.17	0.00
		20%	0.51*	0.45*	0.59*	0.58*	0.55*	0.45*	0.33	0.29	0.23	0.36*	0.36*	0.45*	−0.17	0.00	−0.17	−0.31	−0.31	−0.15
		25%	0.50*	0.46*	0.58*	0.51*	0.54*	0.46*	0.29	0.26	0.20	0.32	0.32	0.33	−0.21	−0.07	−0.21	−0.32	−0.35*	−0.20
		33%	0.40*	0.41*	0.46*	0.41*	0.43*	0.29	0.18	0.18	0.09	0.20	0.21	0.29	−0.14	0.00	−0.14	−0.24	−0.31	−0.17
		50%	0.32	0.38*	0.37	0.40*	0.40*	0.22	0.22	0.19	0.15	0.20	0.23	0.32	−0.08	0.10	−0.08	−0.20	−0.35	−0.27
	Change from Baseline	±1 SD	0.41*	0.40*	0.32	0.34	0.20	0.09	0.47*	0.49*	0.50*	0.45*	0.39*	0.33	0.18	0.23	0.18	0.16	0.14	0.16
		12.5%	0.31	0.28	0.22	0.26	0.12	0.00	0.33	0.38*	0.37	0.26	0.22	0.19	0.07	0.09	0.07	0.06	0.05	0.10
		20%	0.36*	0.37*	0.23	0.25	0.14	0.08	0.48*	0.53*	0.52*	0.46*	0.39*	0.30	0.17	0.22	0.17	0.15	0.13	0.15
		25%	0.27	0.26	0.16	0.18	0.09	0.07	0.49*	0.40*	0.53*	0.47*	0.36*	0.27	0.20	0.19	0.20	0.22	0.23	0.20
		33%	0.28	0.29	0.18	0.19	0.11	0.00	0.46*	0.41*	0.50*	0.44*	0.31	0.23	0.27	0.23	0.27	0.27	0.31	0.23
		50%	0.16	0.19	0.08	0.20	0.17	0.12	0.35	0.29	0.37	0.33	0.29	0.22	0.22	0.19	0.22	0.27	0.23	0.22
	Variance	±1 SD	−0.19	−0.14	−0.21	−0.09	−0.16	−0.15	−0.07	0.14	0.00	−0.09	0.00	−0.01	0.32	0.14	0.32	0.38*	0.33	0.27
		12.5%	−0.24	−0.19	−0.37*	−0.26	−0.29	−0.29	0.00	0.09	0.07	−0.07	−0.11	−0.19	0.22	0.19	0.22	0.40*	0.34	0.29
		20%	−0.24	−0.22	−0.34	−0.25	−0.27	−0.22	−0.06	−0.07	0.00	−0.10	−0.09	−0.15	0.40*	0.22	0.40*	0.52*	0.49*	0.45*
		25%	−0.22	−0.20	−0.31	−0.23	−0.28	−0.20	−0.05	−0.07	0.00	−0.09	−0.08	−0.20	0.36*	0.26	0.36*	0.46*	0.47*	0.40*
		33%	−0.24	−0.23	−0.32	−0.28	−0.32	−0.23	−0.09	−0.06	0.00	−0.12	−0.14	−0.23	0.30	0.22	0.30	0.39*	0.43*	0.29
		50%	−0.08	−0.10	−0.15	−0.20	−0.29	−0.17	0.07	0.00	0.15	0.00	−0.12	−0.27	0.22	0.19	0.22	0.33	0.40*	0.22

			POMS-V Score																	
			Raw Score						Change from Baseline						Variance					
		Threshold	±1 SD	12.5%	20%	25%	33%	50%	±1 SD	12.5%	20%	25%	33%	50%	±1 SD	12.5%	20%	25%	33%	50%
POMS-F score	Raw score	±1 SD	0.29	0.20	0.24	0.28	0.30	0.36	0.25	0.20	0.23	0.27	0.24	0.05	−0.12	−0.10	0.00	−0.07	−0.12	−0.05
		12.5%	0.29	0.19	0.22	0.33	0.35	0.38*	0.32	0.28	0.29	0.33	0.28	0.10	−0.14	−0.10	0.00	−0.07	−0.17	−0.10
		20%	0.23	0.15	0.12	0.21	0.18	0.22	0.25	0.22	0.23	0.31	0.26	0.15	0.00	−0.07	0.11	0.00	−0.04	0.00
		25%	0.30	0.26	0.21	0.28	0.20	0.20	0.28	0.19	0.20	0.27	0.27	0.20	0.00	−0.13	0.05	0.00	−0.08	−0.07
		33%	0.26	0.17	0.18	0.16	0.07	0.12	0.34	0.23	0.27	0.32	0.27	0.17	0.16	0.06	0.14	0.08	0.04	0.00
		50%	0.23	0.19	0.22	0.20	0.17	0.12	0.25	0.10	0.15	0.13	0.12	0.02	−0.01	−0.10	0.00	−0.07	−0.06	−0.07
	Change from Baseline	±1 SD	0.22	0.29	0.22	0.34	0.23	0.39*	0.31	0.39*	0.23	0.20	0.17	0.09	−0.22	−0.29	−0.22	−0.20	−0.23	−0.30
		12.5%	0.15	0.19	0.22	0.33	0.34	0.48*	0.40*	0.38*	0.37*	0.33	0.28	0.19	−0.14	−0.19	−0.07	−0.07	−0.17	−0.19
		20%	0.23	0.22	0.17	0.26	0.22	0.30	0.44*	0.37*	0.35	0.42*	0.35	0.22	−0.11	−0.15	0.00	−0.06	−0.09	−0.15
		25%	0.20	0.20	0.21	0.23	0.16	0.20	0.50*	0.39*	0.41*	0.46*	0.43*	0.27	0.00	−0.07	0.00	0.00	−0.04	−0.07
		33%	0.26	0.23	0.27	0.24	0.14	0.23	0.34	0.23	0.32	0.36*	0.34	0.23	0.08	0.00	0.00	−0.04	−0.07	−0.12
		50%	0.08	0.10	0.08	0.07	0.00	0.02	0.24	0.19	0.22	0.27	0.29	0.12	0.27	0.10	0.15	0.07	0.06	−0.07
	Variance	±1 SD	0.21	0.08	0.07	0.07	0.06	0.05	0.15	0.08	0.07	0.12	0.15	−0.04	0.16	0.16	0.25	0.16	0.15	0.21
		12.5%	0.29	0.09	0.07	0.07	0.11	0.10	0.23	0.19	0.15	0.19	0.23	0.00	0.14	0.19	0.30	0.20	0.12	0.19
		20%	0.23	0.15	0.06	0.11	0.09	0.08	0.18	0.15	0.06	0.10	0.13	0.00	0.21	0.07	0.23	0.15	0.09	0.15
		25%	0.10	0.07	−0.05	−0.04	−0.08	−0.07	0.22	0.19	0.10	0.18	0.23	0.07	0.28	0.13	0.31	0.28	0.24	0.27
		33%	0.18	0.06	−0.05	−0.04	−0.04	0.06	0.23	0.23	0.13	0.19	0.20	0.12	0.25	0.17	0.31	0.28	0.21	0.12
		50%	0.08	−0.10	−0.08	−0.07	−0.06	0.02	0.32	0.19	0.22	0.27	0.23	0.12	0.27	0.29	0.37	0.27	0.17	0.02

The Benjamini–Hochberg correction was applied to all *p*-values. Bolded tau-b values indicate comparisons of the same thresholds between each measure.

†Three different approaches (Raw Score, Change from Baseline, and Variance) defined Resilient and Vulnerable groups based on sleep restriction performance within each measure.

‡SD = standard deviation. Kendall's tau-b correlation coefficients are presented.

*$p < 0.05$.

POMS-V score Variance approaches and tau-b values were moderate (τ_b = 0.40–0.46; p = 0.012–0.029; Table 3). All other Kendall's tau-b comparisons between KSS score and POMS-V score approach categorizations when compared at the same threshold were nonsignificant (τ_b = −0.34 to 0.32; p = 0.060–1.000; Table 3). Table 3 shows detailed results of tau-b values between KSS score and POMS-V score approach categorizations across all thresholds, whereby bolded tau-b values indicate comparisons at the same threshold.

POMS-V score versus POMS-F score When compared at the same threshold, Kendall's tau-b correlations were significant at the 12.5% and 25% thresholds for comparisons between the POMS-V score Change from Baseline and POMS-F score Change from Baseline approaches and tau-b values were weak to moderate (τ_b = 0.38–0.46; p = 0.012–0.047; Table 3). All other Kendall's tau-b comparisons between POMS-V score and POMS-F score approach categorizations when compared at the same threshold were nonsignificant (τ_b = −0.22 to 0.35; p = 0.056–1.000; Table 3). Table 3 shows detailed results of tau-b values between POMS-V score and POMS-F score approach categorizations across all thresholds, whereby bolded tau-b values indicate comparisons at the same threshold.

Discussion

In the current study, we compared resilience and vulnerability of subjective states to sleep loss using three approaches and six thresholds. Generally, we found that all three approaches defined resilience and vulnerability similarly for subjective fatigue, whereas only the Raw Score and Change from Baseline approaches were comparable for subjective sleepiness, and none of the three approaches were comparable for subjective vigor. Additionally, fatigue and vigor scores captured resilience and vulnerability relatively similarly to sleepiness scores, yet they were less related to each other. The Variance approach revealed the lowest concordance with the other approaches overall. When comparing scores between the Res and Vul groups by study day, we found that Res groups defined by the Raw Score approach had significantly better scores than the respective Vul groups consistently throughout the study, whereas results from the Change from Baseline and Variance approaches were more variable depending on the measure, threshold, or day. Importantly, only the Raw Score approach consistently distinguished Res and Vul groups at baseline, during sleep loss, and during recovery for all metrics evaluated; thus, we recommend raw scores as a useful categorization method. To our knowledge, this is the first study to systematically compare multiple approaches and thresholds of categorizing individuals as resilient and vulnerable to sleep loss based on their subjective sleepiness, fatigue, and vigor ratings during chronic SR, and to examine whether such resilience or vulnerability is maintained during a subsequent recovery sleep opportunity.

Using KSS scores, only the Raw Score and Change from Baseline approaches grouped individuals similarly, with the strongest correlations at the ±1 *SD*, 25%, and 33% thresholds. Additionally, Res groups created by the Raw Score approach had significantly lower KSS scores than the respective Vul groups at all thresholds on all days of the study, whereas Res groups created by the Change from Baseline approach had significantly lower KSS scores than the respective Vul groups at all thresholds during sleep deprivation days and variably during recovery at the less restrictive thresholds (i.e. 25%, 33%, and 50%). Interestingly, Res groups created by the Variance approach had lower KSS scores than the respective Vul groups only at some thresholds during TSD. This general lack of significant differences in scores is plausible in the context of our findings that the Variance approach was not significantly correlated with the Raw Score approach for KSS scores. Altogether, individuals who reported low sleepiness during SR had little increase or a decrease in sleepiness from baseline, whereas variability in sleepiness scores during SR was less related to the other approaches. Our results suggest a quartile or tertile threshold may be most appropriate to categorize resilient and vulnerable groups based on KSS score.

POMS-F scores categorized individuals similarly for all three approaches, although correlations were strongest between the Raw Score and Change from Baseline approaches (except for the ±1 *SD* threshold). Moreover, Res groups created by the Raw Score approach had significantly lower POMS-F scores than the respective Vul groups at all thresholds on all study days. However, Res groups created by the Change from Baseline approach had significantly lower POMS-F scores than the respective Vul groups at all thresholds during sleep deprivation days and variably during recovery (although never at the ±1 *SD* threshold), whereas Res groups created by the Variance approach had lower scores than the respective Vul groups at most thresholds during baseline and sleep deprivation and variably during recovery. Individuals who reported low fatigue during SR had little increase or a decrease in fatigue from baseline, and reported stable fatigue levels throughout SR. Overall, POMS-F scores reliably categorized individuals into distinct resilient or vulnerable groups based on subjective fatigue during sleep loss regardless of the approach used, with the ±1 *SD* threshold emerging as the least reliable.

Using POMS-V scores, none of the three approaches grouped individuals similarly; interestingly, the Raw Score and Variance approaches grouped individuals in a discordant manner. Furthermore, Res groups created by the Raw Score approach had significantly higher POMS-V scores than the respective Vul groups at all thresholds on all study days. Interestingly, Res groups created by the Change from Baseline approach had significantly lower POMS-V scores than the respective Vul groups at all thresholds during baseline and variably during recovery, and Res groups created by the Variance approach also had significantly lower scores than the respective Vul groups at all thresholds on all study days. The lack of significant differences during sleep deprivation between Res and Vul groups created by the Change from Baseline approach makes sense in the context of our findings that the Change from Baseline and Raw Score approaches grouped individuals dissimilarly for POMS-V scores and suggests that controlling for baseline scores may reveal that differences in vigor during sleep loss may be explained by baseline levels. Similarly, since Res groups defined by the Variance approach had lower vigor than Vul groups, this is consistent with our findings that the Raw Score and Variance approaches also categorized participants dissimilarly. Thus, individuals who reported high average vigor during SR also reported unstable vigor levels during SR, whereas individuals who reported low average vigor showed greater stability. Therefore, given that the approaches did not categorize groups similarly, particular prudence is needed when determining how to define resilience and vulnerability using subjective vigor. It is also important to note the lack of ±1 *SD* threshold groups for categorizations by the Raw Score and Variance approaches, which suggests that this threshold may not be as useful or reliable for evaluating resilience and vulnerability based on subjective vigor.

Since individual differences in subjective states during sleep loss are robust and stable across repeated sleep loss bouts [13, 14], our Raw Score approach results for all three measures during SR were expected. Similarly, although we categorized resilience and vulnerability based on SR scores, the general pattern of Res versus Vul group differences was similar between SR and TSD for all three measures, as was expected given individual differences when exposed to both chronic SR and TSD [12, 14]; future studies should explore categorizations based on TSD scores. Additionally, one study reported lingering objective behavioral attention differences between resilient and vulnerable groups during acute recovery from sleep deprivation related to the adenosine A_1 receptor [75]. However, for the first time, our results indicate differences in extended recovery profiles for subjective sleepiness, fatigue, and vigor following sleep loss for resilient and vulnerable groups by various approaches and thresholds. Moreover, while differences between resilient and vulnerable individuals related to baseline have been explored using intraclass correlations [12, 13], our results suggest that further research is needed to determine whether change from baseline approaches reliably define resilient and vulnerable groups for each subjective metric. Importantly, the observed differences between Res and Vul group raw scores on each individual day of the study, including during baseline, SR, recovery, and TSD, suggest that scores under each of these conditions may indicate how individuals would experience subjective states during chronic SR. This is particularly informative for real-world settings, such as the typical 5-day work or school week during which many individuals experience chronic partial sleep loss due to demanding schedules and other societal factors [5, 31].

Notably, categorization by the Variance approach revealed the fewest similarities as compared with the other approaches for all measures. We posit this weak relationship may be related to time-of-day variation in subjective ratings that may be only captured by the Variance approach [5, 32–34, 36], as well as to the notion that variability is a multifaceted construct with task-dependent relationships to raw scores [27, 76]. Given these results, we would not recommend using the Variance approach to assess subjective resilience and vulnerability, though further exploration of the poor characterization of resilience and vulnerability to sleep loss using variability in subjective scores is needed.

Furthermore, we found that POMS-F and POMS-V scores captured resilience and vulnerability relatively similarly to KSS scores but were less comparable to each other. Individuals who reported low sleepiness during SR also reported low fatigue, and individuals who reported low sleepiness and/or fatigue during SR also reported little increase or a decrease in sleepiness and/or fatigue from baseline. Additionally, individuals who reported low sleepiness during SR also reported high vigor, individuals who reported little increase or a decrease in sleepiness from baseline also reported little decrease or an increase in vigor, and individuals who reported minimal variance in sleepiness during SR also reported minimal variance in vigor. Unlike the aforementioned comparisons, POMS-F and POMS-V score categorizations were not comparable, which suggests that individuals who are resilient or vulnerable using fatigue as defined by any approach do not similarly exhibit resilience or vulnerability using vigor, and that the constructs of fatigue and vigor may not be closely related, despite deriving from the same questionnaire.

Our study had a few limitations. First, the approaches and thresholds we used do not constitute an exhaustive list of methods for defining resilience or vulnerability to sleep loss using subjective measures. Second, our sample consisted of predominantly African American healthy adults between the ages of 21 and 49 years old; thus, we cannot generalize our findings to other racial and/or ethnic populations, to populations with clinical disorders, or to adolescents or to older adults. Third, studies have found little correspondence of resilience and vulnerability to sleep loss between objective and subjective domains [8, 13, 14, 77–80], making it difficult to generalize our findings to objective metrics. Fourth, we created Res and Vul groups using averaged raw scores across all five SR days, and then assessed differences between the groups' averaged raw scores on each individual day of the study. Despite using raw scores for categorization and analysis of group differences, as other studies also have done [11, 16–19], our findings of group differences on each study day are meaningful and justified, especially during baseline, recovery, and TSD days, which notably were not used for categorization. Moreover, using the same methods to define resilience/vulnerability to sleep loss as assessed by lapses on the Psychomotor Vigilance Test [81], a key objective outcome metric, revealed that all three categorization approaches successfully created distinct Res and Vul groups across the study based on raw scores [82], thus further underscoring that our methods are sound, and our results are justified. Lastly, we did not directly assess the impact of time-of-day fluctuations on performance, since we used averaged scores; however, the Variance approach served as a proxy of such time-of-day effects on subjective sleepiness, fatigue, and vigor scores, in that participants would exhibit greater variation in scores if they were more sensitive to time-of-day effects [5, 31–36].

Raw self-rated scores provide consistent differences between resilient and vulnerable individuals under both sleep-deprived and rested conditions; thus, we recommend this approach as a useful method of categorization. With that said, researchers should still exercise caution when categorizing and determining an individual's resilience or vulnerability to sleep loss using subjective measures, since an individual who exhibits resilience or vulnerability on one subjective measure by one approach at a certain threshold does not necessarily exhibit resilience or vulnerability in a similar manner on other subjective measures. While previous findings suggest that sleepiness, fatigue, and vigor are three distinct states that are not identically affected by sleep loss [83, 84], other studies suggest associations between these subjective constructs [13, 14, 85–88]. Although our results generally suggest distinctions between sleepiness, fatigue, and vigor, further research is needed to better understand potential differences in resilience and vulnerability between various states within the subjective domain.

Importantly, our results have implications related to biomarkers and countermeasures for individual differences in subjective states during sleep loss, which have been previously explored [5, 9, 16, 89]. Considering the associations between high subjective sleepiness or fatigue and increased accident risk [52–55, 90], poor medical performance [56, 91, 92], and genetic links to narcolepsy [89], as well as the association between poor emotional responses to sleep deprivation and future health risks [93], evaluation of subjective state resilience and vulnerability is critical to the recommendation of personalized mitigation strategies related to real-world settings. Self-rated assessments are particularly useful in today's fast-paced world, allowing for rapid and reliable assessments of an individual's capability to perform necessary tasks in sustained attention-dependent operational settings, such as the military [94, 95], transportation services [54, 57], and emergency services [96], among others, thus further adding to the criticality of such research.

Supplementary Material

Supplementary material is available at *SLEEP* online.

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Disclosure Statement

None declared.

Data Availability

The data underlying this article will be shared on reasonable request to the corresponding author.

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