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Accelerometer-derived 'weekend warrior' physical activity pattern and brain health

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Extensive evidence shows the beneficial effect of adhering to a regular physical activity (PA) pattern on brain health. However, whether the 'weekend warrior' pattern, characterized by concentrated moderate-to-vigorous PA (MVPA) over 1–2 days, is associated with brain health is unclear. Here, we perform a prospective cohort study including 75,629 participants from the UK Biobank with validated accelerometry data. Individuals were classified into three PA patterns using current guideline thresholds: inactive (<150 min week^{-1} of MVPA), weekend warrior (≥150 min week^{-1} with ≥50% of total MVPA occurring within 1–2 days) and regularly active (≥150 min week^{-1} but not meeting weekend warrior criteria). We find that the weekend warrior pattern is associated with similarly lower risks of dementia, stroke, Parkinson's disease, depressive disorders and anxiety compared to a regularly active pattern. Our findings highlight the weekend warrior pattern as a potential alternative in preventive intervention strategies, particularly for those unable to maintain daily activity routines.

Existing evidence suggests that PA is associated with lower risks of neurological and psychiatric conditions, including dementia, stroke, Parkinson's disease (PD), depressive disorders and anxiety disorders[1–4]. Notably, previous studies have predominantly measured PA in terms of duration and intensity, aligning with the World Health Organization (WHO) guidelines for PA[5]. However, there is a noticeable research gap regarding the frequency aspect of PA. Specifically, the effectiveness of concentrated MVPA in 1 to 2 days per week—regardless of whether these days fall on the weekend or not, commonly known as the 'weekend warrior' pattern[6]—in maintaining brain health remains uncertain compared to more evenly distributed MVPA.

Given the constraints imposed by modern lifestyles, which often limit PA duration during working hours, adults are increasingly adopting the weekend warrior pattern. And the increasing prevalence of brain disorders[7] in an aging population, coupled with the intractability and irreversibility of these conditions, underscores the urgent need for prioritizing primary prevention strategies to promote brain health in public health initiatives. Exploring the potential association between the weekend warrior exercise pattern and brain health is of great importance.

The present studies investigating the association between different patterns of PA and health outcomes remain limited[8–11]. A study conducted in the National Health and Nutrition Examination Survey (NHANES) cohort found that individuals engaging in the weekend warrior exercise pattern and those who were regularly active both exhibited a reduced risk of depression compared to their inactive counterparts[12]. The findings from two prospective cohort studies demonstrated similar benefits in reducing mortality for individuals who engaged in the weekend warrior pattern and those who were regularly active[8,9]. However, these studies relied on self-reported PA data, which are prone to recall bias and might not accurately reflect actual PA levels. To our knowledge, only two studies have used accelerometer-derived data to examine the weekend warrior pattern, focusing on mortality and cardiovascular diseases[11,13], leaving the

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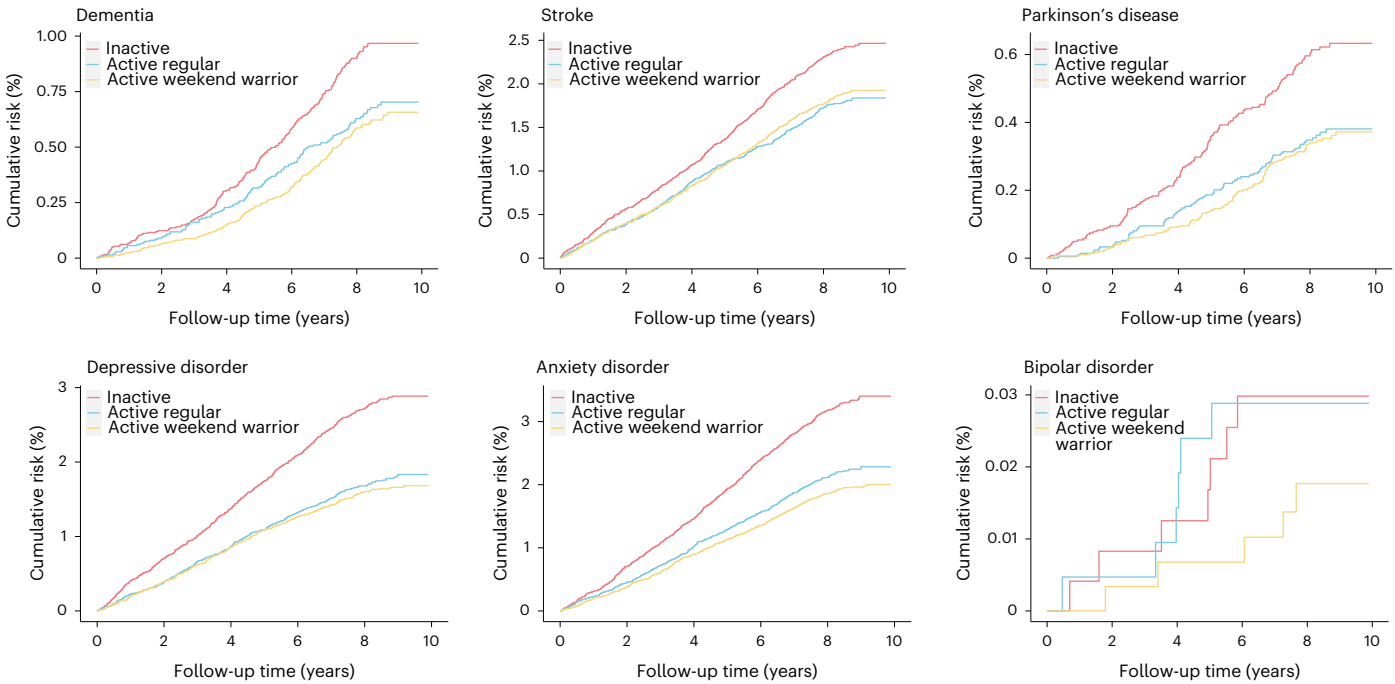

Fig. 1 | The cumulative risk of incident brain disorders stratified by activity pattern using an activity threshold of ≥150 min of MVPA per week (guideline-based). Plots depicting the crude cumulative risk of brain-related disorder events, stratified by accelerometer-derived activity pattern (inactive, red; active regular, blue; active weekend warrior, yellow). Each plot uses the guideline-based threshold for activity (≥150 min of MVPA per week).

relationships between such objectively measured data and brain health unexplored.

To bridge these research gaps, this prospective cohort study leveraged accelerometer data from the UK Biobank to unravel the associations between different PA patterns and the incidence of brain disorders, including dementia, stroke, PD, depressive disorders, anxiety disorders and bipolar disorders (Supplementary Fig. 1). This study also evaluated whether this association was influenced by other risk factors, including sociodemographic characteristics, lifestyle behaviors and health conditions.

Results

Population characteristics

The present study included 75,629 participants, with an average age of 61.8 years (s.d. = 7.9) and a male proportion of 44.6%. Participants' baseline characteristics, categorized by PA patterns, are detailed in Supplementary Table 1. The participants were categorized into three patterns: an inactive pattern, which accounted for 32.2% (24,365 individuals); a regularly active pattern, which accounted for 28.2% (21,291 individuals); and a weekend warrior pattern, which constituted the largest proportion at 39.6% (29,973 individuals). The distribution of daily MVPA for weekend warrior and regularly active individuals is graphically depicted in Supplementary Fig. 2. In general, 'weekend warriors' exhibit notable higher levels of MVPA on their most active 1–2 days compared to the remaining 5 days, whereas the regularly active group shows a more uniform distribution of MVPA.

Association of physical activity patterns with brain health

During an 8.4-year median follow-up period (interquartile range 7.9–8.9), 530 individuals were diagnosed with dementia, 1,468 with stroke, 319 with PD, 1,507 with depressive disorder, 1,794 with anxiety disorder and 18 with bipolar disorder. Kaplan–Meier curves for each PA pattern revealed that the cumulative risk of developing brain disorders was highest among inactive participants and lowest for those following the weekend warrior pattern, except for stroke and bipolar disorders (Fig. 1).

Significant associations between PA patterns and the risk of brain disorders were observed at the guideline-based threshold (Fig. 2 and Supplementary Table 2). Compared to inactive participants, those following the weekend warrior pattern were associated with lower risks of dementia, stroke, PD, depressive disorder and anxiety disorder, with hazard ratios (HRs) and 95% confidence intervals (CIs) from the basic model being 0.74 (0.60–0.90), 0.79 (0.70–0.90), 0.55 (0.43–0.71), 0.60 (0.53–0.67) and 0.63 (0.57–0.71), respectively. Similar risk reductions were observed in the regularly active pattern, with the result for dementia not reaching statistical significance (HR, 0.91; 95% CI, 0.73–1.13). The comparisons of model 1 (basic model) with model 2 (sociodemographical model), 3 (lifestyle model), 4 (health status model) and 5 (full model) suggested that most covariates had minimal impact on the associations between PA patterns and brain disorders. However, no significant association was found between PA patterns and bipolar disorder, potentially attributed to the limited number of cases of bipolar disorder.

Activity patterns and brain health at various thresholds

Regardless of the threshold defining the active group, both activity patterns (regularly active and weekend warrior) showed lower risks of PD, depressive disorders and anxiety disorders in comparison to the inactive group (Fig. 3 and Supplementary Table 3). Specifically, at the 25th percentile threshold of ≥115.2 min week^{-1} of MVPA, there was a significant reduction in the risk for PD by 46% (27%–60%) and 48% (32%–60%) among individuals who engaged in regular PA and those who were weekend warriors, respectively. At the 50th percentile threshold of ≥244.8 min week^{-1} of MVPA, similar risk reductions were observed at rates of 36% (13%–53%) and 41% (22%–56%), while at the 75th percentile threshold of ≥417.6 min week^{-1} of MVPA lower risk, these figures were even more pronounced, with risk reductions reaching levels of approximately 35% (4%–56%) and 44% (16%–63%). Similar trends were also observed in the outcomes of depressive and anxiety

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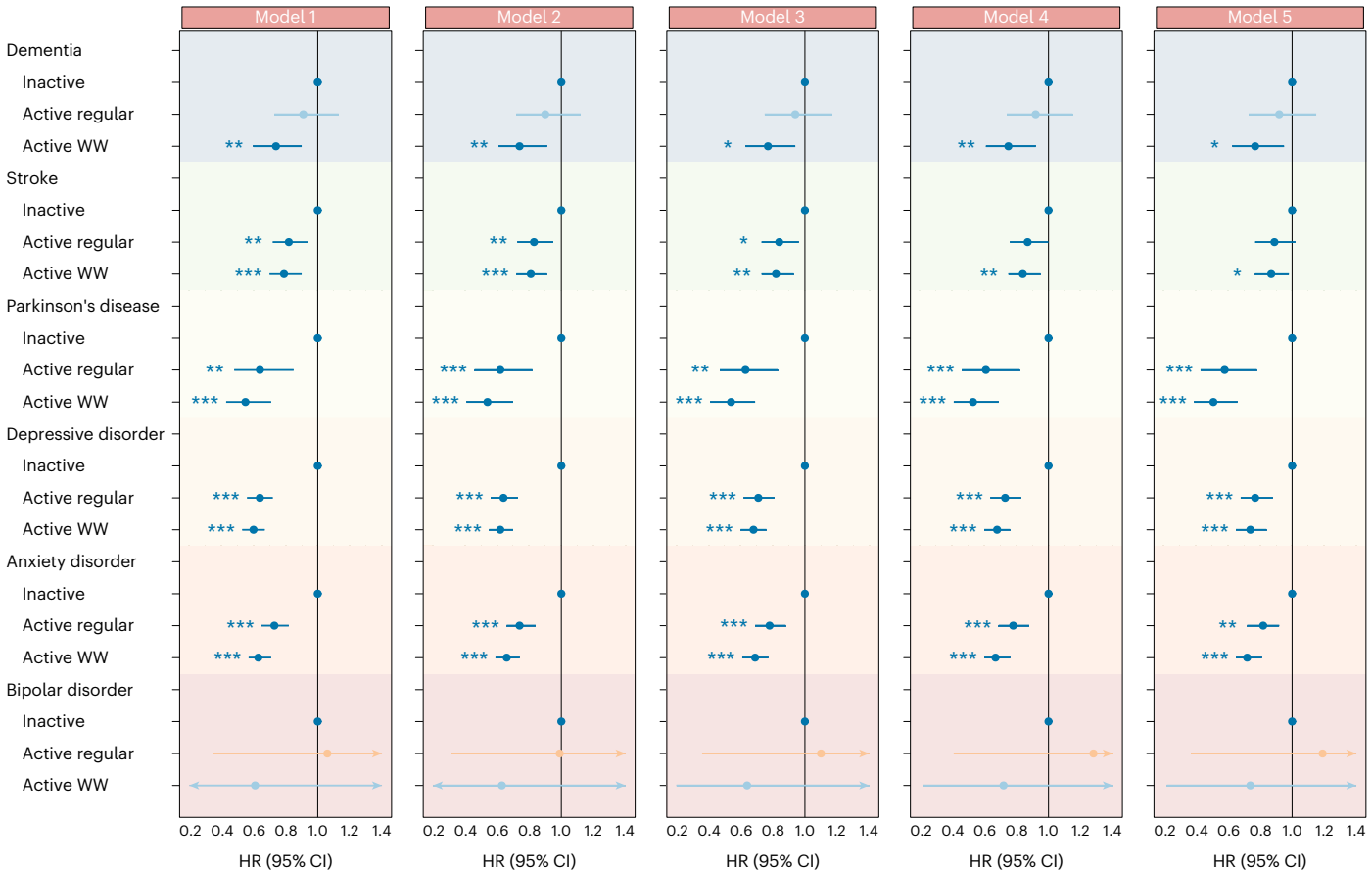

Fig. 2 | Association between PA pattern and incident brain disorders in models with different sets of covariates and the fully adjusted model. We used participants (n = 75,629) from the UK Biobank with valid accelerometer data in the analyses. Model 1 (basic) was adjusted for age and sex. Model 2 (sociodemographics) was adjusted for age, sex, ethnicity, TDI and education level. Model 3 (lifestyle) was adjusted for age, sex, smoking status, alcohol intake frequency, diet scores and sleep scores. Model 4 (health conditions) was adjusted for BMI, history of diabetes, history of hypertension and history of cancer. Model 5 was a fully adjusted model with adjustment for all covariates mentioned above. Inactive was defined as <150 min of MVPA per week. Active weekend warrior (WW) was defined as ≥150 min of MVPA per week and had ≥50% of total MVPA over 1–2 days. The dots represent the mean HR and the widths of the lines extending from the center points represent 95% CIs. Darker blue dots signify HR values below 1 with statistical significance, while lighter blue dots denote HR values less than 1 that lack statistical significance. Yellow dots indicate HR values exceeding 1. Arrows in blue or yellow suggest that the corresponding lower or upper CI extends beyond the displayed abscissa range. Wald tests were used in the analyses to obtain the two-sided and unadjusted P values. *P < 0.05, **P < 0.01, ***P < 0.001.

disorders. However, the associations of the weekend warrior pattern with the risks of dementia and stroke became no more significant at the threshold of the 50th and 75th percentile of total MVPA.

Subgroup analyses

In the fully adjusted model, individuals aged both below and above 65 years demonstrated a comparable reduction in the risk of developing dementia, PD, depressive disorders and anxiety disorders (Fig. 4 and Supplementary Table 4). There was no statistically significant age-related interaction observed in PA patterns (all P values for interaction >0.05). This trend remained consistent across both sexes, with similar risk reductions for brain disorders observed in both females and males (P value for interaction >0.05). For example, the weekend warrior pattern was significantly associated with a reduced risk of PD in younger individuals (HR, 0.50; 95% CI, 0.26–0.93), older individuals (HR, 0.48; 95% CI, 0.36–0.64), females (HR, 0.44; 95% CI, 0.27–0.72) and males (HR, 0.55; 95% CI, 0.40–0.75). These findings indicate that individuals of various sexes and age groups benefit similarly from reduced risk of brain disorders when following the weekend warrior pattern. The subgroup analyses by ethnicity revealed that the association between PA patterns and brain disorders in White participants aligns with the main analysis (Supplementary Table 5). However, because of the limited sample sizes of other ethnic groups for these populations, we were unable to obtain statistically significant estimates for these populations.

Sensitivity analyses

The sensitivity analyses generally concurred with the primary findings. Further adjustments in the models, including occupation and sedentary time yielded consistent results (Supplementary Tables 6 and 7). The results of the analysis additionally adjusting for total MVPA volume did not materially change, although the associations were attenuated and lost statistical significance for dementia and stroke (Supplementary Table 8). Characterizing the weekend warrior pattern as comprising ≥75% of total MVPA over 1–2 days resulted in adjusted HRs (95% CI) of 0.66 (0.45–0.98) for dementia, 0.76 (0.61–0.96) for stroke, 0.38 (0.22–0.67) for PD, 0.59 (0.45–0.75) for depressive disorders and 0.74 (0.60–0.91) for anxiety disorders. Alternative definitions of the weekend warrior pattern, such as accumulating ≥50% of total MVPA over 1–2 consecutive days and accumulating ≥50% of total MVPA over 1–2 weekend days, also produced consistent results (Supplementary Table 9). The results remained generally consistent with the main analyses when we excluded individuals who had the outcomes within the first

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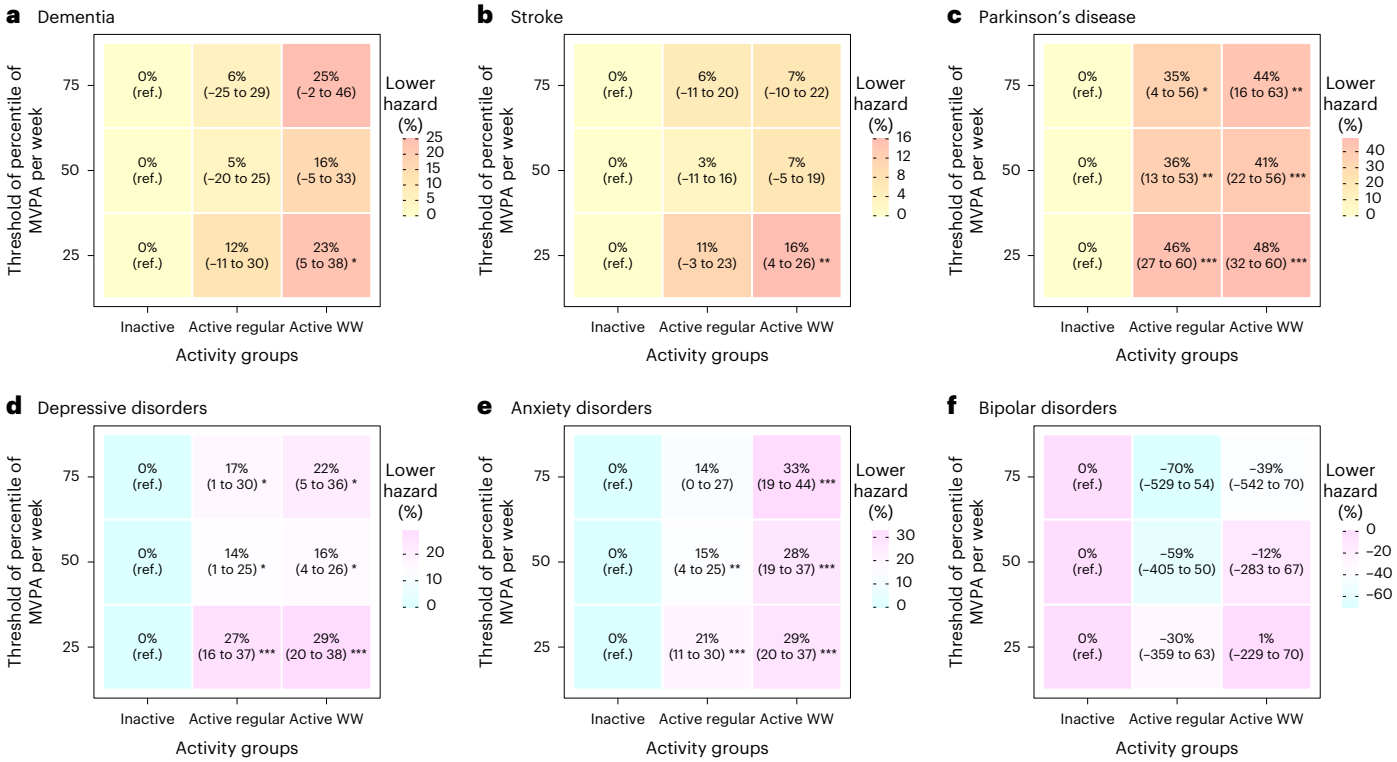

Fig. 3 | Association between PA pattern and incident brain disorders using different thresholds of total MVPA volume per week. a–f, Associations of PA patterns with dementia (**a**), stroke (**b**), PD (**c**), depressive disorders (**d**), anxiety disorders (**e**) and bipolar disorders (**f**). The numerical values depicted represent the percentage reduction in hazard associated with each outcome relative to the inactive group. The first row uses a yellow and red color scheme to show various neurological disorders under investigation. In contrast, the second row uses blue and purple color schemes to present multiple psychiatric disorders. All are adjusted for age, sex, ethnicity, TDI, education level, smoking status, alcohol intake frequency, diet scores, sleep scores, BMI, history of diabetes, history of hypertension and history of cancer. Wald tests were used in the analyses to obtain the two-sided and unadjusted *P* values. Inactive was defined as the threshold of MVPA per week (25th, 50th or 75th percentile of total MVPA volume). Active weekend warrior was defined as at or above the MVPA threshold and had ≥50% of total MVPA over 1–2 days. $^{*}P < 0.05$, $^{**}P < 0.01$, $^{***}P < 0.001$. ref., reference; WW, weekend warrior.

1 or 2 years of follow-up (Supplementary Table 10), when missing data were imputed by chained equations (Supplementary Table 11), when we also included the wear time and the season of wear as covariates in the models (Supplementary Table 12), when we used baseline data for covariates (Supplementary Table 13) and when we adjusted for health conditions that may influence the ability to perform PA (Supplementary Table 14).

Discussion

In this large population-based cohort study, we found that adhering to the weekend warrior pattern was similarly associated with a lower risk of both neurological diseases and psychiatric disorders in regularly active individuals. The findings were almost consistent after adjusting for various covariates, including sociodemographical factors, lifestyles and health conditions.

Previous prospective studies investigating the associations between various PA patterns with health outcomes have indicated that the weekend warrior pattern may confer similar benefits to a regularly active pattern. A synthesized study incorporating 11 cohort samples revealed that participants following a weekend warrior pattern were associated with a 30% reduction in all-cause mortality compared to inactive individuals[8]. Similarly, another prospective cohort study involving 350,978 US adults suggested that engaging in either weekend warrior or regular PA patterns was associated with lower all-cause mortality rates compared to inactive individuals[9]. A cross-sectional analysis reported significant decreases in psychological distress among both 'weekend warrior' and regular daily exercise participants[10]. The aforementioned conclusions, however, were derived from self-reported PA data, which may be susceptible to misclassification. Additionally, the heterogeneity in PA questionnaires used across studies could potentially lead to incomparable results. Our study advances previous research by using wrist-worn accelerometers to precisely capture the duration and frequency of MVPA from the largest accelerometer cohort study. To date, only two prospective cohort studies have used accelerometers to measure PA patterns and examined their associations with mortality and cardiovascular disease[11,13]. The present study elucidates the associations between PA patterns, especially the weekend warrior pattern and overall brain health.

In this study, baseline characteristics revealed that the weekend warrior participants constituted the largest segment of the total population (29,973 out of 75,629 (39.6%)), a proportion markedly higher than that observed in previous studies based on self-reported data (2,341 out of 63,591 (3.7%); 9,992 out of 350,978 (3.0%); refs. 8,9). Conversely, a population-based study using accelerometer data from NHANES reported that 32.3% of participants in their study were weekend warriors, supporting our findings[13]. This notable discrepancy suggests a greater accuracy in assessing PA patterns using device-measured data compared to self-reported data. Furthermore, these findings indicate an increasing prevalence of the weekend warrior pattern among adults, possibly attributed to their busy lifestyle and the convenience of this pattern. Consequently, further research is needed to explore the association between weekend warrior patterns and a wide range of health outcomes to demonstrate the potential health benefits of these exercise patterns.

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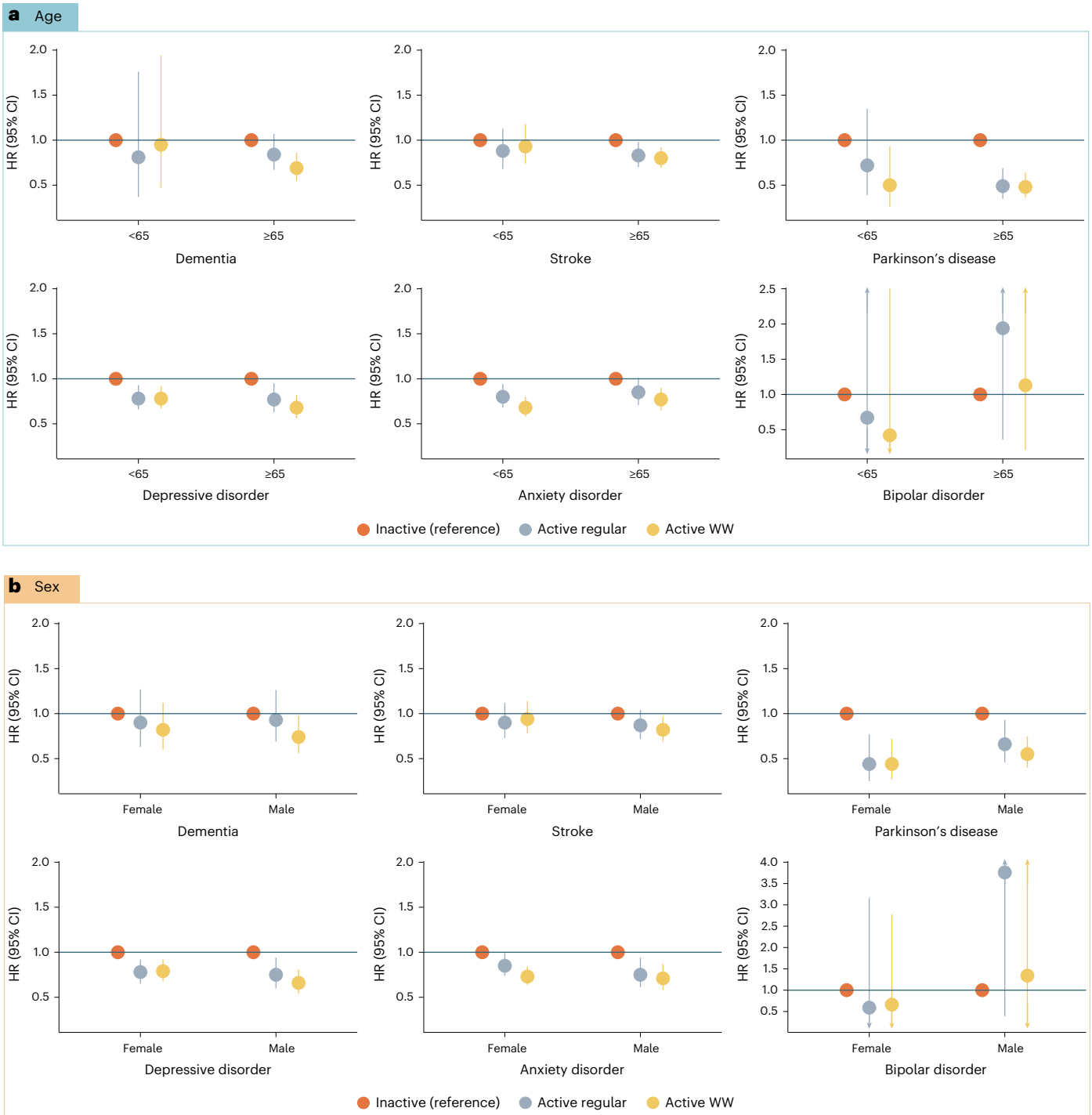

Fig. 4 | Association between PA pattern and incident brain disorders stratified by age and sex. We used participants (n = 75,629) from the UK Biobank with valid accelerometer data in the analyses. **a**, Associations of PA patterns with brain health stratified by age (<65 and ≥65 years). **b**, Associations of PA patterns with brain health stratified by sex (female and male). All were adjusted for age (except for subgroup of age), sex (except for subgroup of sex), ethnicity, TDI, education level, smoking status, alcohol intake frequency, diet scores, sleep scores, BMI, history of diabetes, history of hypertension and history of cancer. Inactive was defined as <150 min of MVPA per week. Active weekend warrior was defined as ≥150 min of MVPA per week and had ≥50% of total MVPA over 1–2 days. The dots represent the mean HR and the widths of the lines extending from the center points represent 95% CIs. Wald tests were used in the analyses to obtain the two-sided and unadjusted P values. WW, weekend warrior.

Our study emphasizes the comparable benefits of both the weekend warrior pattern and the regularly active pattern for brain health relative to an inactive pattern. After adjustment for daily lifestyle and health conditions, the weekend warrior individuals meeting the guideline-based threshold (≥150 min of MVPA per week), were associated with 23%, 13%, 49%, 26% and 28% reduced risks for dementia, stroke, PD, depressive disorder and anxiety disorder, respectively. Considering that some individuals may not achieve the recommended volume of PA and given the lack of well-defined optimal levels of MVPA measured by wrist-based accelerometers[14], we conducted analyses

across populations with varying basal exercise levels and tested different thresholds for active groups to reaffirm our main findings. The results potentially indicated that the weekend warrior pattern, irrespective of adhering to the WHO PA guidelines of 150 min of MVPA per week, was associated with reduced risks of neurological diseases and psychiatric disorders. Sensitivity analysis including additional adjustments for total MVPA volume, further demonstrated that both weekend warrior and regularly active participants at equivalent MVPA volumes were associated with a lower risk of brain disorders. However, it is important to note that the associations between the weekend warrior pattern and the risks of dementia and stroke diminished and lost statistical significance when using the 50th and 75th percentile thresholds for total MVPA volume and after extra adjustment for MVPA volume. This lack of significance in the results may be attributed to the option of thresholds for activity patterns, thereby emphasizing the necessity for further studies to classify PA patterns through a more objective and sophisticated approach.

The current study showed that the weekend warrior pattern was associated with a similar lower risk of a variety of brain disorders with regularly active pattern, suggesting potential common mechanisms underlying these disorders. For instance, an animal study demonstrated that the weekend warrior model helps prevent depression-like cognitive and behavioral changes by inhibiting inflammatory processes and improving antioxidant capacity[15], which are the key pathways linking PA and brain disorders, such as dementia, depression and anxiety[16,17]. Additionally, exercise could have a positive impact on several supporting systems for brain health, such as neurogenesis, central nervous system metabolism and angiogenesis[18]. For example, concentrating most PA volume over 1–2 days may enhance the expression of neuroprotective growth factors, increase the neurotrophic factors released and reduce damage to dopaminergic neurons[19,20]. In addition to this, a study measuring the binding of opioids in the brain through positron emission tomography found that prolonged exercise released endogenous opioids in the human brain[21]. These underlying shared mechanisms might explain the significant risk reduction associated with the weekend warrior pattern observed in this study for various brain disorders. Future research efforts should focus on clarifying the specific mechanisms behind these associations and replicating our findings in different populations.

Despite the growing recognition of the importance of exercise for maintaining good health, a considerable 27.5% of adults worldwide still fail to meet the current public health guidelines for PA[22]. A population-attributable fraction analysis has revealed that, if there is no change in physical inactivity, an alarming 499.2 million new cases of preventable major non-communicable diseases including stroke, dementia and depression would emerge globally by 2030 (ref. 23). One potential factor contributing to this phenomenon is the limited availability of time for regular PA due to demanding lifestyles. Robust findings from this study underscore the benefits of the weekend warrior PA pattern on brain health, especially in lowering the risk of dementia, PD, depressive disorder and anxiety disorder. For many adults, this PA pattern could be more feasible than structured and regular exercise due to its minimal time requirement. Therefore, the weekend warrior pattern may be able to be incorporated into future public health policy and PA guidelines for adults.

The strengths of this study include its large-scale sample size, prospective design, several sources for outcomes collection, meticulous control of diverse covariates and comprehensive sensitivity analyses. Notably, the duration and frequency of MVPA were objectively measured by an accelerometer in a free-living environment, which reduced the recall bias and misclassification inherent in questionnaire-based data collections. Nonetheless, this study has several limitations. First, due to the low response rate (5.5%) of the UK Biobank and the additional selection criterion of the accelerometer sub-study, we acknowledge the presence of selection bias in our study, which cannot be completely ruled out in an observational study[24]. However, existing evidence suggested that this lack of representativeness does not impact the valid and generalizable assessments of exposure–disease relationships[25]. Second, the representativeness of a 7-day accelerometer measurement for longer-term behaviors[26], particularly in PA patterns, remains uncertain. However, a previous validation study showed a strong correlation between 7-day measurements and PA over periods of up to 3.7 years (ref. 27). Third, although a wrist-worn accelerometer is a validated measure of PA at varying levels in free-living conditions, this device used to detect MVPA may not fully capture certain activities, such as stationary cycling, potentially leading to inaccuracies[28,29]. Fourth, while several thresholds and alternative definitions were used to classify participants into different PA groups, the definition of weekend warrior remained subjective in this study. More sophisticated approaches for classifying PA patterns are encouraged for future research. Fifth, it is important to note that relying on medical records for diagnosing diseases could introduce bias and may underdiagnose conditions, especially for late-life disorders like dementia. However, the use of a multisource dataset in this study helped to capture a full spectrum of disorders, potentially minimizing bias. Sixth, it should be noted that while the subgroup analysis by age (<65 and ≥65 years) suggested consistent associations between the weekend warrior pattern and reduced risk of brain disorders across mid-life and late-life stages, caution should be exercised in generalizing these findings to population outside the specific age range, such as individuals aged 80 years and above. This limitation arises because the participants included in our study ranged from 43 to 79 years. Seventh, as with any observational study, the possibility of residual or unmeasured confounding cannot be entirely dismissed, despite the inclusion of a wide array of confounders in our analysis. Eighth, we cannot conclude causal associations between PA patterns and brain health. Furthermore, although we conducted analyses to mitigate the likelihood of reverse causation, we cannot completely rule out its potential influence in observational studies of this nature. Finally, PA patterns may vary with chronological age. This study only assessed PA levels at a single timepoint using accelerometers, which may not accurately capture changes in PA patterns over the entire lifespan of an individual. Future studies should use accelerometer data with repeated measurements to better elucidate the impact of changes in PA patterns on brain health.

In conclusion, our study using accelerometer data from UK Biobank demonstrates that engaging in a weekend warrior pattern, characterized by concentrated bouts of high-volume MVPA within 1 to 2 days, is associated with a similar risk reduction for brain disorders as the regularly active pattern.

Methods

Population

This study used data from the UK Biobank, which received approval from the North West Multi-centre Research Ethics Committee (R21/NW/0157) and the Biomedical Research Ethics Committee of Hangzhou Normal University (approval no. 200400001). All participants gave written informed consent and signed the informed consent to be linked to national electronic health-related datasets[25]. No compensation was provided to participants. The UK Biobank is a comprehensive longitudinal and prospective cohort study, encompassing >500,000 participants recruited from 22 centers across England, Scotland and Wales between 2006 and 2010. Participants completed a range of interviews and questionnaires covering sociodemographic factors, lifestyles, health status and physical assessments[30]. In a specific phase between May 2013 and December 2015, a subset of 240,000 UK Biobank participants were invited via email to participate in an accelerometer-based study. The response rate was 44%, with devices dispatched for 106,053 participants and data obtained from 103,666 of these participants.

In this study, we initially included 103,666 participants with available accelerometry information. Exclusions were implemented for

individuals who withdrew from the UK Biobank (n = 6), had poorly calibrated accelerometer data (n = 11), insufficient wear time (<3 days of data or no wear data in each 1-h period of the 24-h cycle; n = 6,984), had unrealistically high acceleration values (mean acceleration values >100 mg; n = 13), without available data on daily MVPA (n = 1,159), with missing covariates values (n = 4,048), had less than a full week of acceleration data (n = 3,862) and presented with pre-existing brain disorders (n = 11,954). Finally, 75,629 participants with valid data were included in the primary analysis. The flowchart of this study is provided in Supplementary Fig. 3.

Physical activity patterns

Participants in the accelerometry study were instructed to wear Axivity AX3 triaxial accelerometers on their dominant wrist for 1 week[31]. The device recorded acceleration at 100 Hz with a dynamic range of ±8 g. Data were aggregated into 5-s epochs, representing the mean vector magnitude. Further details on data collection and processing methodologies are provided in ref. 31. The analysis used a previously published machine learning algorithm to accurately classify MVPA from other movement behaviors (including light-intensity PA, sedentary behaviors and sleep) based on data collected from wrist-worn accelerometers[32]. The accuracy of this machine learning method has been validated in a UK-based sample with a mean accuracy of 88% and Cohen's kappa of 0.80 (ref. 32).

The duration of MVPA in this study was determined by calculating the daily proportion of time spent engaging in MVPA (Field ID 40045). The participants were categorized according to their level and pattern of PA following the WHO PA guidelines, including inactive (<150 min of MVPA per week) and physically active (≥150 min of MVPA per week) groups. The physically active group was further divided on the basis of the highest volume of PA over a 2-day period, which did not necessarily need to be on a weekend: the weekend warrior group (in which at least 50% of total MVPA occurred within 1–2 days) and the regularly active group (in which at least 50% of total MVPA was distributed over >2 days). The conventional PA recommendations primarily rely on self-reported PA data, which may potentially differ from data obtained through device measurements. Therefore, in our primary analysis, we explored several thresholds to define active patterns, including ≥25th percentile (115.2 min week^{-1}), ≥50th percentile (244.8 min week^{-1}) and ≥75th percentile (417.6 min week^{-1}) of the total MVPA weekly volume.

Brain disorders

This study focused on a variety of brain disorders, including neurological diseases (dementia, stroke and PD) and psychological disorders (depressive disorders, anxiety disorders and bipolar affective disorders). Brain disorders were ascertained using the dataset of 'first occurrences' in the UK Biobank (category ID 1712), which is a multisource dataset that integrates information from various sources, including primary care data, hospital inpatient records, death registers and self-reported medical conditions. The accuracy of routinely collected healthcare data for identifying brain disorders has been demonstrated through previous research, indicating its reliability as a method[33–35]. These multisources data were mapped to three-character International Classification of Disease (ICD) codes. Particularly, dementia cases were defined as all-cause dementia in this study, containing Alzheimer's disease, vascular disease and other unspecified neurodegenerative dementias (ICD-10 codes F00-F03 and G30). The stroke cases encompassed ischemic stroke (including transient cerebral ischemic attacks and cerebral infarction), hemorrhagic stroke (including intracerebral and subarachnoid hemorrhage) and stroke not specified as hemorrhagic or infarction (ICD-10 codes G45, G46, I60, I61, I63 and I64). Comprehensive details on the assessment of brain disorders are provided in Supplementary Table 15. The follow-up visits for participants were extended from the date of accelerometry completion until either the earliest diagnosis of any brain disorder or the end of the follow-up period (1 May 2023), whichever occurred first.

Covariates

We have identified 13 covariates, both at the individual and population levels, which may exert an influence on the association between patterns of PA and brain health, based on existing knowledge and literature[11,17,36]. These included age at PA data collection (years), sex (female and male), ethnicity (White and others), Townsend deprivation index (TDI), education attainment (college or university degree and others), smoking status (never, former and now), alcohol intake frequency (daily or almost daily, three or four times a week, once or twice a week, one to three times a month, special occasions only and never), diet quality, sleep pattern, body mass index (BMI), history of diabetes (yes and no), history of hypertension (yes and no) and history of cancer (yes and no).

TDI is a composite indicator of unemployment, car ownership, house ownership and household overcrowding, which represent the level of deprivation with higher values indicating higher deprivation[37]. Information on ethnicity, education attainment, smoking status, alcohol intake frequency, diet quality and sleep pattern were obtained from touchscreen questionnaires or verbal interviews. Diet quality was reflected in a diet score based on the frequency of consumption of fruits, vegetables, fish, processed meat, unprocessed red meat, whole grains and refined grains, with higher scores indicating a healthier diet quality[38,39]. The sleep pattern assessment encompassed chronotype, sleep duration, insomnia, snoring and excessive daytime sleepiness, using a scoring system ranging from 0 (poorer) to 5 (healthier)[40]. BMI was calculated as the weight in kilograms divided by the square of the height in meters, which was obtained by trained nurses. History of diabetes or hypertension was obtained from self-reported questionnaires. History of cancer was identified on the basis of the hospital inpatient records, using the ICD-10 C00–C99, except for C44. To mitigate temporal bias due to the temporal fluctuations of certain covariates (such as education attainment, smoking status, alcohol intake frequency, diet quality, sleep pattern and BMI), these variables were recorded at the timepoint closest to the accelerometry measurement (Supplementary Fig. 4).

Statistical analysis

The baseline characteristics of participants, categorized by different patterns of PA at the threshold of PA guideline (≥150 min week^{-1}), were summarized as mean and s.d. for continuous variables and number and percentage for categorical variables.

The associations between PA patterns and brain disorders were tested using the Cox proportional hazards regression, with results presented as HRs and 95% CI. Schoenfeld residuals were used to verify the proportional hazard assumption for Cox models and no violation was observed. Five distinct models were constructed, each adjusting for different covariates to evaluate the independence of the association from various factors. All tested models included age and sex as covariates. Model 1 (basic model) adjusted only for age (continuous; in years) and sex (binary; male and female). Model 2 (sociodemographical model) included ethnicity (binary; White and others), TDI (continuous) and education attainment (binary; college or university degree and others) as covariates. Model 3 (lifestyle model) incorporated smoking status (multiclassification; never, former and now), alcohol intake frequency (multiclassification; detailed above), diet quality (continuous; 0 to 7 scores) and sleep pattern (continuous; 0 to 5 scores). Model 4 (health status model) included BMI (continuous; in kg m^{-2}), history of diabetes (binary; yes and no), history of hypertension (binary; yes and no) and history of cancer (binary; yes and no) as covariates. Model 5 (full model) comprised all aforementioned covariates. Kaplan–Meier plots stratified by activity patterns were generated to show the cumulative incidence of each

outcome. Fully adjusted models were used with various thresholds of total MVPA volume (25th, 50th and 75th percentiles) to explore the potential modification of these associations by the basal exercise volume. Subgroup analyses were conducted to investigate whether age (<65 and ≥65 years), sex (female and male) and ethnicity (White and others) moderated the association between PA patterns and brain disorders.

To evaluate the robustness of our primary findings, we performed a series of sensitivity analyses. First, we further adjusted the models to account for participants' occupational characteristics, as individuals who are employed may be more inclined to adopt the weekend warrior pattern. Second, we incorporated sedentary time derived from accelerometers into the models to account for its potential impact both on exercise patterns and brain disorders. Third, considering the impact of PA volume on PA patterns, we further explored the association by adjusting for total MVPA volume. Forth, we used alternative definitions of the weekend warrior pattern, including the accumulation of ≥75% of total MVPA over 1–2 days, ≥50% of total MVPA over 1–2 consecutive days and ≥50% of total MVPA over 1–2 weekend days, to test whether the association between weekend warrior and brain health would change. Fifth, to mitigate reverse causation risk, we excluded individuals who had the outcomes of interest within the first 1 and 2 years of follow-up. Sixth, missing covariate values were addressed using chained multiple imputation and we repeated our main analyses in a complete dataset. Seventh, we included the wear time and the season of wear as additional covariates in the models to account for potential variance in the exposure and to enhance estimate precision. Eighth, we performed an analysis using baseline covariates data to prevent bias introduced by postmeasurement adjustments. Finally, given the potential impact on the ability to perform PA, some health conditions including myocardial infarction, asthma, chronic obstructive pulmonary disease, chronic kidney disease and motor neuron disease were also adjusted for in our models.

All the analyses were conducted using STATA 16 statistical software (Stata Corp) and R software (v.4.1.3). The statistical significance was set as $P < 0.05$ (two-sided test).

Statistics and reproducibility

This study was a longitudinal and prospective population-based cohort study. No statistical test was used to predetermine the sample sizes but our sample sizes are similar to those reported in previous publications using accelerometer data from cohorts used in the present study[11]. Participants without valid accelerometer data to derive PA pattern were excluded from the cohort. Furthermore, we excluded participants with any missing information on covariates and with diagnoses of any brain disorders of interest at baseline. The flowchart and exclusion criterion are detailed in Supplementary Fig. 3. The experiments were not randomized and the investigators were not blinded to allocation during experiments and outcome assessment. Data collection and accelerometry analyses were performed before the initiation of the present study. The statistical tests used are given in the legends of the figures. Data distribution was assumed to be normal but this was not formally tested.

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

The main data used in this study were accessed from the publicly available UK Biobank Resource (https://www.ukbiobank.ac.uk) under application no. 79095, which cannot be shared with other investigators because of data privacy laws. The UK Biobank data can be accessed by researchers on the application. Source data are provided with this paper.

Code availability

Scripts used to perform the analyses are available at https://github.com/Chen-jie-Xu/UKB_weekend_warrior_brain_health.git.

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Author contributions

J.M., Z.C., Y.W. and C.X. contributed to the conception, study design and ideas. J.M. and Z.C. collected, assembled the data and performed the statistical analysis. J.M., Z.C., T.D, Y.W. and C.X. conducted results interpretation. J.M. and Z.C. wrote the first and successive drafts of the manuscript. T.D, Y.W. and C.X. revised the manuscript for important intellectual content. C.X. and Y.W. obtained fundings. C.X. and Y.W. provided administrative, technical and logistic support. All authors reviewed the manuscript and approved the final version.

Competing interests

The authors declare no competing interests.

Additional information

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Our web collection on statistics for biologists contains articles on many of the points above.

Software and code

Policy information about availability of computer code

Data collection	Data obtained from the UK Biobank are available on application at www.ukbiobank.ac.uk/register-apply (79095).
Data analysis	All the analyses were conducted using STATA 16 statistical software (Stata Corp LLP, college station, TX) and R software (version 4.1.3). Scripts used to perform the analyses are available at https://github.com/Chen-jie-Xu/UKB_weekend_warrior_brain_health.git.

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Research involving human participants, their data, or biological material

Policy information about studies with human participants or human data. See also policy information about sex, gender (identity/presentation), and sexual orientation and race, ethnicity and racism.

Reporting on sex and gender	The reported sex of participants was accessed through UK Biobank data-field 31, and included as a covariate in the statistical analyses for all models. In addition, we conducted a subgroup analyses on sex and found that the association between weekend warrior pattern and the risks of brain disorders was similar in both females and males (p-value for interaction >0.05). Gender was not considered in this study.
Reporting on race, ethnicity, or other socially relevant groupings	Participants' ethnicity was sourced from the UK Biobank data-field 21000 and incorporated as a covariate in the statistical evaluations. Participants self-identified their ethnic background during the baseline period (2006 - 2010), with further details available within the UK Biobank.
Population characteristics	A total of 75,629 participants with valid accelerometer data were included in this study, with a mean age of 61.8 years (standard deviation = 7.9 years). The baseline characteristics of participants, stratified by physical activity patterns, are presented in Table 1. Descriptive statistics were calculated as mean (SD) for continuous variables and number (percentage) for categorical variables. The participants were categorized into three patterns: an inactive pattern, which accounted for 32.2% (24,365 individuals); a regularly active pattern, which accounted for 28.2% (21,291 individuals); and a weekend warrior pattern, which constituted the largest proportion at 39.6% (29,973 individuals). Participants adhering to the weekend warrior pattern generally exhibited better health and were more likely to be male compared to their inactive counterparts.
Recruitment	The UK Biobank is a large population-based prospective cohort that recruited approximately 500,000 participants aged 37-73 years in the United Kingdom. Participants visited one of 22 assessment centers across England, Scotland, and Wales. 236,519 UK Biobank participants were invited to participate in an accelerometer study. Between 2013 and 2015, 240,000 invitations were sent to them for PA measurement by accelerometers, with a response rate of 44%. Devices were dispatched for 106,053 participants and, of these, data were received from 103,666. Raw accelerometer data from 103,666 participants were further processed by the UK Biobank accelerometer expert working group. In addition, according to the exclusion criteria, 75,629 participants with valid data were finally included in the current study.
Ethics oversight	UK Biobank has approval from the North West Multi-centre Research Ethics Committee as a Research Tissue Bank (RTB) approval. This approval means that researchers do not require separate ethical clearance and can operate under the RTB approval. Informed consents were obtained from all participants. The ethical approval for the UK Biobank is extensively detailed and described online: https://www.ukbiobank.ac.uk/learn-more-about-uk-biobank/about-us/ethics. This current study was undertaken under project 79095.

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Sample size	Firstly, we included 103,666 participants with available accelerometer data. Exclusions were implemented for individuals who withdrew from the UK Biobank (n = 6), had poorly calibrated accelerometer data (n = 11), insufficient wear time (<three days of data or no wear data in each 1-hour period of the 24-hour cycle; n = 6,984), displayed unrealistically high acceleration values (mean acceleration values >100 mg; n = 13), with missing covariates values (n = 4,048), had less than a full week of acceleration data (n = 3,862), and presented with pre-existing brain disorders (n = 11,954). Finally, 75,629 participants with valid data were included in the primary analysis. These sample size are sufficient for the analyses according to the previous published studies using data from UK Biobank. No statistical method was used to predetermine sample size.
Data exclusions	The data exclusion criteria were documented in Methods and Supplementary Fig. 2. The exclusion criteria are as follows: 1) those who withdrew from the UK Biobank; 2) those who did not had device-measured PA data; 3) those who had insufficient wear time; 4) those who displayed unrealistically high acceleration values ; 5) those who had missing information on covariates; 6) those who had less than a full week of acceleration data; 7) those who presented with pre-existing brain disorders at baseline.
Replication	This is a study based on data from the UK Biobank large-scale cohort. We have not repeated the analysis in other populations. However, we used different statistical methods to verify our findings: (1) controlling for a wide range of potential covariates; (2) comprehensive sensitivity analyses. Our main findings were quite robust and consistent across these analyses.
Randomization	Not applicable (It is population-based longitudinal cohort study and not a randomized clinical trial).

Blinding	Not applicable (It is population-based longitudinal cohort study and not a randomized clinical trial).

Reporting for specific materials, systems and methods

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Methods

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Plants

Seed stocks	NA
Novel plant genotypes	NA
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