**Estimating treatment effects of physical activity on subdomains of mental health: A propensity score analysis among a global sample of 341,956 adults**

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**Abstract**

CONTENT

**Introduction**

Suboptimal mental well-being and mental health problems have proven to be a significant burden on the global population. Approximately 29% of individuals have experienced a common mental disorder during their lifetime, with a 9.6%, 12.9%, and 10.7% lifetime prevalence for mood, anxiety, and substance-use disorders, respectively [1]. Global burden of mental disorders in 2019 was estimated at 125.3 million disability-adjusted life-years (DALY) – an increase from 80.8 million DALYs in 1990 [2]. Moreover, lost productivity due to poor mental health is estimated to cost the global economy $2.5T annually and is projected to more than double over the next decade, reaching $6T by 2030 [3]. The COVID-19 pandemic may also have conferred a toll on population mental health and wellbeing worldwide. Evidence from reviews is somewhat mixed, but findings suggest there has been an increase in depressive and anxiety symptoms most consistently in younger and female cohorts, [4-10].

Emerging evidence in addition to recent findings from the COVID-19 pandemic suggests younger age cohorts may be at greater risk for poor mental health and well-being [11, 12]. For example, a recent report showed that younger adults living in the US consistently report the lowest scores on all domains of mental well-being, including happiness, health, meaning and purpose, character, social relationships, and financial stability, with a linear pattern of improvements in well-being observed with increased age [13]. These findings are in contrast to previous work that had demonstrated an inverted-U relationship between age and mental well-being in which mental well-being was lowest in middle adulthood [14]. Further, the onset of an estimated half of first mental disorders occurs by age 18, which speaks to the pervasiveness of mental health challenges experienced in early adulthood [15]. Evidently, more research is needed to better understand these age-related trends from a global perspective, including a focus on protective factors that may moderate the relationship between age and mental well-being.

Physical activity is one aspect of our lifestyle that has received increasing attention for its potential to promote mental well-being as well as assist in the prevention and management of mental health disorders. Observational and experimental evidence consistently shows a relationship between higher levels of physical activity and benefits across various mental health outcomes, including, but not limited to depression [16-21], anxiety [22-24], and general mental health and well-being [25-27]. For example, using a matching procedure in a large cross-sectional dataset, Chekroud, et al. (28) showed that engaging in physical exercise in the past month was associated with 43.2% lower self-reported days with poor mental health over that period. Despite these robust findings, particularly for depression and anxiety, physical activity remains an underutilized treatment tool among clinical practitioners [29]. The inclusion of physical activity – albeit as an alternative and/or complementary treatment – in several recent national guidelines for the treatment of depression holds promise for promoting greater uptake in primary care services [30-33].

While evidence supports the importance of physical activity for preventing and/or reducing a range of mental health problems and improving overall well-being, for some other mental symptoms and disorders (e.g., bipolar disorder, schizophrenia), the evidence is less suggestive of benefits, or remains unclear [34-39]. More recently, however, researchers have observed considerable overlap in symptomology across the most commonly classified mental health disorders, which illustrates the complexity and heterogeneous nature of mental health as a construct [40, 41]. Such knowledge has sparked the development of novel measures – the Mental Health Quotient (MHQ) for example – to address these considerations. Yet, due to their recency, these instruments have seldom been utilized.

One promising avenue in which comprehensive measures of mental health can be applied is in studies examining the specific aspects of mental health that physical activity may especially favor. At present, there is a paucity of literature in this area – to our knowledge only one study has investigated symptom-level effects [42]. Findings stemming from such studies have the potential to improve precision in the promotion of mental well-being and treatment of mental health problems and therefore may have important implications for clinical outcomes [43-45]. Determining whether physical activity is associated with differential effects for certain aspects of mental health across the lifespan is but one fruitful area of inquiry to pursue for the purpose of improving population-level mental health and well-being.

The purpose of the present study was to estimate the treatment effect of physical activity engagement on overall mental health in a large global sample, as well as various subdomains of mental health, while statistically accounting for a range of observed covariates using a machine learning technique underutilized in exercise psychology and behavioral medicine.

**Methods**

**Study Sample and Data Collection**

This cross-sectional study used data from the Mental Health Million (MHM) project, an on-going online study with the purpose of assessing global mental well-being through administration of the Mental Health Quotient. The sample for our present study included 341,956 participants from 229 countries who completed the MHM survey between December 31st, 2021 and October 14th, 2022. The start of this period coincided with the launch of Version 3 of the MHQ. Additional information concerning the MHM project and recruitment strategy may be found elsewhere [46]. This study involved secondary analysis of existing non-identifiable data and therefore Institutional Research Ethics Board approval was not required.

**Measures**

**Mental health.** The MHQ is a 47-item instrument designed to assess a comprehensive range of common attributes found across widely used existing mental health assessment tools in a single questionnaire to estimate overall mental well-being and functioning in the population. Items were developed by consolidation of 170 symptoms coded from 126 commonly used assessment tools covering depression, anxiety, bipolar disorder, ADHD, post-traumatic stress disorder, obsessive-compulsive disorder, addiction, schizophrenia, eating disorders and autism spectrum disorder. The MHQ is unique from other psychiatric tools in that the items assess level of functioning and impact on one’s life associated with each mental health element, as opposed to frequency, duration, or severity of symptoms. The questionnaire took an average of 14 minutes for participants to complete.

Responses from the 47 items were used to compute the MHQ, which represents an overall score of mental health and well-being. The MHQ originally ranged from -100 to +200, however, the lower limit was recently expanded to -166 to improve the distribution of scores that previously demonstrated a floor effect at the lower bound. Scores on the MHQ can be classified into six levels of functioning, with negative scores indicating clinical risk and positive scores representing normal range: Clinical (≤-50), At Risk (-50 to <0), Enduring (0 to <50), Managing (50 to <100), Succeeding (100 to <150) and Thriving (150 to 200). To compute the overall score, individual item responses were weighted to reflect the nonlinearity of risk associated with increases in symptom severity, as well as the differential risk associated with different symptoms (e.g., suicidal thoughts vs irritability).

In addition to the overall MHQ score, scores for six broad subcategories of mental health and wellbeing were computed: Core Cognition, Adaptability and Resilience, Mood and Outlook, Drive and Motivation, Social Self, and Mind-Body Connection (see Table 1). Subcategory scores ranged from -100 to +200, and were computed by a weighted average of scores from 10 to 24 relevant symptom items based on a review of cognitive and brain functioning models [46].

Table 1. Descriptions of the Subdomains of the MHQ

|  |  |
| --- | --- |
| MHQ Subcategory | Description |
| Core Cognition | The ability to function effectively and independently on a moment-to-moment basis. It includes brain functions such as attention, memory, learning, and self-control. Abnormal aspects of core cognition include severe or extreme forms of mental confusion, obsessive thoughts, sensory sensitivity, compulsive behaviors, psychosis, and hallucinations. |
| Adaptability and Resilience | The ability to synthesize and make sense of complex sets of events and situations and display a longer-term perspective in thoughts and behavior. It includes brain functions such as decision making, creativity, problem solving, planning, and adaptability to change. Abnormal forms of complex cognition are associated with extreme risk-taking and severe intolerance to change. |
| Mood and Outlook | The ability to manage and regulate emotions effectively and encompasses feelings of distress like fear, anxiety, anger, irritability, guilt, and sadness. It also includes the ability to have a constructive or optimistic outlook for the future. Abnormal forms of emotional functioning include uncontrollable crying, night terrors, severe temper outbursts, extreme phobias, uncontrollable panic attacks, highly traumatic flashbacks, intense mania, or suicidal intentions. |
| Drive and Motivation | The ability to work toward desired goals and to initiate, persevere, and complete activities in daily life. It is associated with interest, curiosity, and motivation and is also related to overall energy levels. Abnormal forms of drive and motivation include severe addictions that cause harm or extreme withdrawal from activities or social interaction. |
| Social Self | The ability to interact with, relate to, and see oneself with respect to others. It includes factors like confidence, communication skills, self-worth, body image, empathy, and relationship building. Abnormal forms of social functioning include excessive unprovoked aggression, a strong sense of being detached from reality, or suicidal intentions. |
| Mind-Body Connection | The regulation of the balance between mind and body to ensure that any mental concerns do not manifest themselves as physical symptoms in the body in a chronic or severe way. It includes functions like sleep, appetite, coordination, physical intimacy, and fatigue. Abnormal forms of mind-body balance can include insomnia or chronic and severe pain, as well as a propensity for infection or frequent physical symptoms (eg, digestive issues) with no obvious physical cause. |

Descriptions adapted from Newson et al. [46]

The MHQ has demonstrated high sample reliability when four randomly selected and demographically similar samples were compared on response distributions, and resulting MHQ distribution [47]. Internal consistency was demonstrated with conceptually similar items having higher correlations than unsimilar items. A subset of participants which took the MHQ twice at least 3 days apart showed strong test-retest reliability as evidenced by a correlation of *r* = 0.84. Validity was assessed by asking a subset of participants additional questions concerning days missed from work and normal activities in the past month due to problems with their physical or mental health. Those who were reporting being employed and scored an overall MHQ between 175 to 200 missed on average 0.2 days of work in the past month, while adults who reporting being employed and who scored between -75 to -100 missed an average of 9.3 days of work.

**Physical activity**: Participants responded to single item that asked: “How regularly do you engage in physical exercise (30 minutes or more)?” Response options included “Rarely/never”; “Less than once a week”; “Once a week”; “Few days a week”; and “Every day”. In line with Chekroud, et al. (28), responses to the physical activity frequency item were recoded into binary groups with participants who reported “Rarely/never” coded as the control (inactive; no exposure to physical activity), and all other responses coded as the treated (physically active; exposure to physical activity).

**Covariates**: To adjust for potential confounders, the following covariates were included in our statistical models: age, biological sex, gender identity, ethnicity, educational attainment, employment status, relationship status, frequency of adequate sleep, frequency of socializing, diagnosis of a medical condition (Y/N), whether they are currently seeking mental health treatment (Y/N), and whether they reported a significant traumatic childhood or adult experience (Y/N). Data inspection revealed considerable missingness for ethnicity (84.2%) and gender identity (98.5%) due to only having been included on surveys for individuals who reported residing in certain countries, and therefore these variables were dropped from our analyses. All items in which participants responded “Prefer not to say” were recoded as missing.

**Statistical Analysis**

All data preprocessing and statistical analyses were done using the statistical software R version 4.1.2 [48] and RStudio (Version 2022.07.2). First, distributions of covariates were balanced between the non-exposure (i.e., Inactive) and exposure (i.e., Physically Active) groups using propensity score weights estimated with generalized boosted modeling (GBM) [49, 50], and implemented in the R Package *WeightIt* [51]. The propensity score is defined as “the conditional probability of assignment to a particular treatment given a vector of observed covariates” [52]. Weighting was preferred over matching procedures for the purpose of preserving sample size. Propensity scores weights were computed based on the Average Treatment effect on the Control (ATC) estimand, which is used to estimate the hypothetical average treatment effect on those who did not receive the treatment. In other words, it is the expected effect of physical activity on those in the sample who are inactive, which would help inform the clinical question on whether mental health practitioners should encourage physical activity in inactive patients. This research question is relevant for mental health practitioners given that individuals with mental health disorders have been shown to be more sedentary and less active than population norms [53]. Treatment effects estimated with propensity score adjustment are unbiased when the strong ignorability assumption is met (i.e., when there are no unobserved confounders, and all observed confounders are included in the model) [52].

GBM is a non-parametric iterative machine learning method which, as implemented in the present study, combines boosting (the sequential combination of weak learners to improve predictions by adapting the errors of the previous model) and regression trees (the weak learners) to generate a smoothed function of estimated propensity scores. This method automatically accommodates non-linearity and complex interactions, and has been shown in previous studies to outperform traditional parametric models such as logistic regression [49, 54, 55]. Several tuning parameters were selected to achieve covariate balancing, as suggested by McCaffrey et al [49]. The Bernoulli distribution was chosen for the loss function the boosted model was to minimize, as our treatment variable was coded as a binary exposure. The number of trees was determined by minimizing the average standardized absolute mean difference in the covariates. The maximum number of trees was set to 10,000 by default, and increased to 20,000 if covariate balancing was not achieved. Missing data was handled by surrogate splitting as described in the *WeightIt* R package documentation [51]. Though unlikely to significantly improve the performance of our procedure [56] weights above 99% were winsorized to reduce potential bias from extreme values. Diagnostics were used to ensure covariates were adequately balanced by assessing the weighted absolute standardized difference in means of covariates between treatment and control group.

For our main analysis, propensity weights were fed into a regression model to estimate the ATC for physical activity on seven outcomes: overall MHQ score, and its six subcategories: Core Cognition, Adaptability and Resilience, Mood and Outlook, Drive and Motivation, Social Self, and Mind-Body Connection. To explore whether the effect of physical activity on mental health differs across age groups, we performed the same analysis on each age group for the MHQ and its six subcategories. Lastly, we estimated the marginal interaction effects of age and physical activity on MHQ to investigate whether an age gradient for mental health exists, and how this may be moderated by physical activity status. In all models, participants were nested within country to account for potential clustering effects.

Several sensitivity analyses were performed to determine whether the inferences of the main analyses were biased due to model misspecification or handling of missing data [57, 58]. First, we computed propensity score weighted regression models that included further adjustment for the full covariate set to allow for doubly robust estimation [59]. Second, instead of handling covariate missingness by surrogate splitting, we first implemented multiple imputation (MI) before the GBM estimation of propensity scores. Third, we estimated ATCs using MI and covariate balancing propensity score (CBPS) weighting, which may outperform GBM if there is a non-complex relationship between treatment and outcome [60]. MI and CBPS are described in greater detail in the Supplementary Materials (Section A). Doubly robust estimation was also computed for these models by including the full covariate set in the multiply imputed, CBPS or GBM weighted regression models. Akin to our main analyses, participants were nested within country for all models.

**Results:**

**Descriptive statistics**

After dropping two cases due to Arabic responses not translating properly, the final sample included 341,956 participants, and was predominantly female (55.3%), post-secondary educated (47.5% with a bachelor’s or graduate degree), employed (47.8%), married (42.5%), and physically active to some degree (60.4%). The sample was also representative across the adult lifespan (18-24 and 55-64 were the most common age ranges selected at 18.91% and 18.50% of the sample, respectively). The mean score for the MHQ was 67.93 ± 72.70 SD. Full descriptive statistics for the sample demographic characteristics, covariates, physical activity, and mental health can be found in Table 2.

After adjusting for propensity score weighting, the effective sample for the treated (active) group was reduced to 140,633.8 (68.13% of unadjusted), yielding an overall effective sample size of 276,158.8 (80.76% of original sample). The effective sample size is the “approximately the number of observations from a simple random sample that yields an estimate with sampling variation equal to the sampling variation obtained with the weighted comparison observation”, and can be interpreted as a conservative lower bound for the adjusted size of the weighted sample [61]. Diagnostics indicated that covariate balance was successfully achieved after GBM and CBPS weighting procedures were implemented (see Supplementary Materials, Section B).

**Physical Activity**

Propensity score weighted models demonstrated physical activity was associated with significant (p < 0.01) treatment effects on overall MHQ scores (ATC = 17.86; 95% CI: 15.07-20.64), which coincided with a small effect size calculated using standard deviations from the unweighted data (standardized mean difference (SMD) = 0.25). Physical activity was also associated with treatment effects for each of the six MHQ subcategories: Core Cognition (ATC = 16.33; 95% CI: 13.87-18.78; SMD = 0.25), Adaptability and Resilience (ATC =17.57; 95% CI: 14.83-20.31; SMD = 0.26), Drive and Motivation (ATC = 15.86; 95% CI: 12.87-18.86; SMD = 0.24), Mood and Outlook (ATC = 15.27; 95% CI: 12.53-18.01; SMD= 0.22), Social Self (ATC = 13.02; 95% CI: 10.18-15.85; SMD = 0.17), and Mind-Body (ATC = 19.25; 95% CI: 16.66-21.84; SMD = 0.31).

**Physical Activity and Age**

Figures 1 and 2 show effects of PA on overall MHQ scores and each subcategory by each age group. Briefly, overall trends showed significant beneficial effects of physical activity on overall MHQ scores and each MHQ subcategory across each age group. Larger effects were observed for young and middle-aged adults as well as those 85+ years of age. Inspection of the estimated effects on the six MHQ subcategories suggest that younger age groups may experience more favorable effects from physical activity for Core Cognition and Adaptability and Resilience, as compared to the other older age groups. All ATCs and standard errors can be found in Supplementary Materials Table 1.

Figures 3 and 4 shows predicted values of overall MHQ scores and each of the six subcategories as a function of age and physical activity engagement, demonstrating consistent increases in mental health with aging, with the exception of 75-84 to 85+ where mental health appears to plateau as evidenced by non-significant changes in both the inactive and active groups. Being physically active was associated with consistently higher mental health across all age groups.

**Sensitivity analyses**

Our sensitivity analyses (see Table 3) demonstrated convergence of the estimated treatment effects of physical activity on mental health across each of the alternative statistical techniques employed when compared to the main GBM results.

**Discussion**

The purpose of the present study was to estimate a treatment effect of physical activity engagement on mental health using the novel comprehensive MHQ instrument, which captures a broad range of clinical mental health symptoms as well as aspects of wellbeing, summarizing them on a single dimension ranging from clinical risk to thriving. Our findings revealed a significant small effect of self-reported physical activity on overall mental health and well-being. Sensitivity analyses revealed this effect was robust after adjusting for covariates using several different statistical methods. These findings are consistent with the existing evidence that has demonstrated beneficial associations between physical activity and various psychological outcomes including severe mental disorders [53], cognitive function [62, 63], emotional skills [64], resilience [65], and quality of life [21, 26]. Our results also align with previous work that has shown favorable effects of physical activity on indicators of mental health are consistent across the adult lifespan [66, 67]. Taken together, these findings further underscore the importance of promoting a physically activity lifestyle to improve population mental health and well-being, which has the potential to significantly reduce the forecasted growing economic costs associated with poor mental health over the next decade.

Findings from the present study also contribute to the body of literature investigating associations between physical activity and mental health through examining specific subcategories of mental health and well-being. Our results showed robust and consistent beneficial effects of physical activity on each of the six subcategories, although it should be noted that physical activity appears to have a significantly stronger relationship with Mind-Body compared to Social Self as evidenced by non-overlapping 95% CIs. The Mind-Body Connection subcategory, in which the largest effects were observed for physical activity, contains items assessing aspects of well-being with benefits robustly related to physical activity, such as pain [68, 69], sleep [70, 71], appetite regulation [72, 73], and fatigue [74, 75]. Conversely, the smallest effect was shown for Social Self, which includes aspects of well-being with less established and robust associations to physical activity such as… empathy and body image [76-79]. Although physical activity is a social pursuit for many across the world, one potential explanation for a smaller effect of physical activity on Social Self is that some individuals prefer to engage in independent activities such as running or cycling alone, thus negating the potential social benefits associated with more group-oriented activities such as team sports and exercise classes. Nevertheless, these findings suggest that physical activity may confer benefits for all aspects of mental health and well-being, with small differences favoring psychophysiological over social aspects.

This study also addressed a knowledge gap regarding a dearth of evidence investigating potential differential effects of physical activity on certain aspects of mental health and well-being across the adult lifespan. Evidence indicated that young and middle-aged adults may experience greater benefits for their overall mental health from physical activity engagement in comparison to older adults. It should be noted that adults 85+ years of age appear to be an exception; however, this group also had the largest confidence interval likely due to a relatively smaller sample. As average levels of physical activity tend to be higher among young and middle-aged adults than older adults [80, 81], a more sedentary lifestyle may be differentially indicative of impairment in younger cohorts, given the bi-directional nature of the physical activity – mental health relationship [REF]. Core Cognition, Drive and Motivation, and Adaptability and Resilience followed the same trend as overall MHQ scores, and thus these specific aspects of mental health and well-being may be more amenable to benefits from adopting a more active lifestyle, whereas the other subcategories seem to demonstrate relatively consistent benefits from physical activity across the adult lifespan. Finally, differences between inactive and active groups across ages were most pronounced in the 85+ age group as evidenced by the largest average marginal effect across all subcategories. This finding makes it clear that physical activity engagement is especially important for maintaining better mental health and well-being in the latest stages of life.

As the body of literature examining associations between physical activity and mental health continues to grow, it is imperative that researchers adopt statistical best practices that can reduce bias and strengthen our inferences. Matching and weighting techniques have received little attention in the fields of exercise psychology and behavioral medicine to date. For example, an advantage of utilizing propensity scores over controlling for covariates in a traditional multivariable linear regression is that the propensity model can deal with non-linear relationships between the covariates and outcome, as well as higher order interactions, and the GBM can handle these interaction terms non-parametrically when estimating the propensity score. As different propensity score estimation methods may perform differentially based on different assumptions and approaches to handle missing data [57, 58, 60], we utilized several combinations of methods in our sensitivity analyses. Our sensitivity analysis revealed minimal deviance in the estimated effects of physical activity on overall MHQ scores across the various covariate adjustment and missing data procedures that were implemented – effect sizes ranged from an SMD of 0.25 to 0.26 Using these various propensity score estimation techniques helped to improve our confidence that the estimated effect was not biased due to misspecification of the propensity model. In doing so, these estimates strengthen the inferences we can make about the relationship between physical activity and mental health. Though strong causal inferences are not indicated by cross-sectional observations, our results converge with existing intervention studies [22, 82-84]. For example, previous meta-analyses of randomized controlled trials on exercise and depression found pooled effect sizes ranging from 0.62 to 0.98 [20, 85, 86]. Compared to previous intervention research, however, our findings may underestimate the true effect of physical activity, yet the size and diversity of our sample may indicate this association is not as strong as randomized controlled trials would otherwise suggest. Regardless, the present findings support and extend the existing literature on the benefits of physical activity engagement across various aspects of mental health. ADD CLINICAL IMPLICATIONS SENTENCE to wrap up paragraph.

Despite several strengths, there are several limitations with the current study. Firstly, unlike true randomization, propensity score weighting does not adjust for unobserved covariates [87]. An unbiased treatment effect assumes that all potential confounders are observed, which is unlikely to be the case in any observational study. Additionally, the covariates included in this analysis were restricted by what was included in the MHM survey. Adjusting for a partial set of confounders may reduce bias, but it is unknown to what extent. Second, the MHQ and its subdomains have yet, to our knowledge, been validated in an independent sample. It would be interesting, for example, to investigate whether the MHQ and its subdomains predict the onset or course of distinct mental disorders. Third, physical activity was self-reported, which can introduce recall errors – particularly among older adults who are more prone to cognitive decline – and social desirability effects [88]. However, researchers need to balance feasibility with practicality and therefore using a self-reported measure of physical activity may be best suited for data collection with a sample of this size and geographic dispersion. Lastly, the MHM project has used convenience sampling to recruit participants, targeted towards individuals who used mental health-related search terms in Google and Facebook. Although the present sample includes individuals from over 200 countries, it may not truly be globally representative, as it would have also overlooked individuals living in regions with limited to no internet access.

**Conclusion**

This cross-sectional study estimated treatment effects of physical activity on several aspects of mental health among a large global sample of adults using advanced covariate balancing techniques to reduce bias in our estimates. Our results demonstrate a significant small effect of self-reported physical activity on a comprehensive measure of overall mental health and well-being, in addition to similar benefits across several specific subcategories of mental health. The strongest associations between physical activity and mental health appear to occur during the early and middle-aged adult life stages, with effects becoming weaker into old age. Collectively, findings further buttress the growing body of evidence in support of promoting physical activity to promote various aspects of mental health and well-being among the population.

The largest differences between the active and inactive groups averaged across ages was for Mind-Body Connection (31.42) and lowest for Core Cognition (24.39) and Social Self (24.90), converging with the treatment effects estimated from the propensity model.

Another interesting finding is that the moderated marginal effects model revealed an age gradient for all mental health subdomains, which aligns with previous findings of Chen and colleagues [13], wherein greater well-being was observed in earlier generations among a nationally representative sample of adults living in the US. Closer inspection of the MHQ subcategories revealed that Mood and Outlook (B = 93.62) and Social Self (B = 94.27) appear to benefit the most from aging. These subcategories are conceptually similar to the two flourishing domains (i.e., Happiness and Life Satisfaction; and Close Social Relationships) that older adults (≥77 years) scored highest on in the study by Chen et al. [13].

* Favorable benefits of physical activity on overall mental health as well as several subdomains (Main effect of PA)
  + How does this compare to chekroud
  + Supports general body of literature demonstrating the benefits of PA
  + Ours results compared to RCTs (compare effect sizes?)
* PE strongest effect on Adaptability and Resilience, lowest on Social Self (is this in line with current literature? Comments on different exercise modalities?) (How PA differed across each subdomain – where are the strongest/weakest effects – why may this be)
  + Implications for precision medicine – PA stands to provide greatest benefits for some outcomes, maybe other behaviors provide greater benefits for others – to be determined in future use of the instrument (MHQ)
* Relatively poor MH in younger ages, confirming Chen 2022 (main effect of age)
* Interaction effects exist, stronger benefits for PA among younger adults.
  + This may be due to them having more to gain due to poorer mental health
  + Comment on implications for population level interventions potentially
* Propensity weighting methods allow us to make stronger causal inferences compared to common regression models (using more advanced techniques)
* Limitations
* Conclusion

Limitations:

Self-reported physical activity behavior – can introduce bias and recall errors

Cross-sectional design – cannot infer causality

Convenience sampling – not truly globally representative despite over 200 countries included

Strong ignorability assumption; propensity scoring assumes all potentially confounding covariates are observed

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**Table 2 Descriptive statistics for the full sample and by each age group**

|  | Total | 18-24 years | 25-34 years | 35-44 years | 45-54 years | 55-64 years | 65-74 years | 75-84 years | 85+ years |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | (*N* = 341,956) | *(n =* 64,648) | *(n =* 47,249) | *(n =* 55,241) | *(n =* 57,259) | (*n* = 63,113) | (*n* = 40*,*881) | (*n* = 12,029) | (*n* = 1,536) |
| Sex |  |  |  |  |  |  |  |  |  |
| Female | 189226 (55.3%) | 39831 (61.6%) | 27344 (57.9%) | 31203 (56.5%) | 30890 (53.9%) | 32729 (51.9%) | 20256 (49.5%) | 6141 (51.1%) | 832 (54.2%) |
| Male | 148624 (43.5%) | 23206 (35.9%) | 19427 (41.1%) | 23584 (42.7%) | 25815 (45.1%) | 29827 (47.3%) | 20299 (49.7%) | 5807 (48.3%) | 659 (42.9%) |
| Other/Intersex | 819 (0.2%) | 268 (0.4%) | 63 (0.1%) | 92 (0.2%) | 163 (0.3%) | 136 (0.2%) | 63 (0.2%) | 14 (0.1%) | 20 (1.3%) |
| Missing | 3287 (1.0%) | 1343 (2.1%) | 415 (0.9%) | 362 (0.7%) | 391 (0.7%) | 421 (0.7%) | 263 (0.6%) | 67 (0.6%) | 25 (1.6%) |
| Education |  |  |  |  |  |  |  |  |  |
| Associate’s Degree | 21259 (6.2%) | 3921 (6.1%) | 2512 (5.3%) | 2643 (4.8%) | 3174 (5.5%) | 4381 (6.9%) | 3398 (8.3%) | 1093 (9.1%) | 137 (8.9%) |
| Bachelor’s Degree | 105724 (30.9%) | 17800 (27.5%) | 19818 (41.9%) | 20404 (36.9%) | 18197 (31.8%) | 17066 (27.0%) | 9753 (23.9%) | 2455 (20.4%) | 231 (15.0%) |
| Graduate Degree | 56764 (16.6%) | 3386 (5.2%) | 8580 (18.2%) | 11690 (21.2%) | 11725 (20.5%) | 11671 (18.5%) | 7423 (18.2%) | 2038 (16.9%) | 251 (16.3%) |
| High School | 77434 (22.6%) | 23451 (36.3%) | 7871 (16.7%) | 9293 (16.8%) | 10880 (19.0%) | 12985 (20.6%) | 9321 (22.8%) | 3155 (26.2%) | 478 (31.1%) |
| Less than High School | 34040 (10.0%) | 6836 (10.6%) | 2902 (6.1%) | 4720 (8.5%) | 5674 (9.9%) | 7249 (11.5%) | 4811 (11.8%) | 1620 (13.5%) | 228 (14.8%) |
| Other | 16246 (4.8%) | 3578 (5.5%) | 2248 (4.8%) | 2552 (4.6%) | 2733 (4.8%) | 2997 (4.7%) | 1649 (4.0%) | 412 (3.4%) | 77 (5.0%) |
| Vocational Certification | 21823 (6.4%) | 1922 (3.0%) | 2613 (5.5%) | 3054 (5.5%) | 3842 (6.7%) | 5487 (8.7%) | 3762 (9.2%) | 1043 (8.7%) | 100 (6.5%) |
| Missing | 8666 (2.5%) | 3754 (5.8%) | 705 (1.5%) | 885 (1.6%) | 1034 (1.8%) | 1277 (2.0%) | 764 (1.9%) | 213 (1.8%) | 34 (2.2%) |
| Employment |  |  |  |  |  |  |  |  |  |
| Employed /Self employed | 163401 (47.8%) | 12630 (19.5%) | 29040 (61.5%) | 39198 (71.0%) | 41026 (71.6%) | 33075 (52.4%) | 7391 (18.1%) | 960 (8.0%) | 81 (5.3%) |
| Homemaker | 31570 (9.2%) | 2260 (3.5%) | 5383 (11.4%) | 8198 (14.8%) | 7162 (12.5%) | 5874 (9.3%) | 2124 (5.2%) | 478 (4.0%) | 91 (5.9%) |
| Not able to work | 7210 (2.1%) | 1212 (1.9%) | 806 (1.7%) | 966 (1.7%) | 1444 (2.5%) | 2193 (3.5%) | 473 (1.2%) | 81 (0.7%) | 35 (2.3%) |
| Retired | 61333 (17.9%) | 102 (0.2%) | 93 (0.2%) | 317 (0.6%) | 1924 (3.4%) | 17194 (27.2%) | 30038 (73.5%) | 10380 (86.3%) | 1285 (83.7%) |
| Studying | 48583 (14.2%) | 40925 (63.3%) | 4306 (9.1%) | 1476 (2.7%) | 1101 (1.9%) | 574 (0.9%) | 149 (0.4%) | 30 (0.2%) | 22 (1.4%) |
| Unemployed | 29859 (8.7%) | 7519 (11.6%) | 7621 (16.1%) | 5086 (9.2%) | 4602 (8.0%) | 4203 (6.7%) | 706 (1.7%) | 100 (0.8%) | 22 (1.4%) |
| Relationship Status |  |  |  |  |  |  |  |  |  |
| Divorced/ Separated | 32484 (9.5%) | 876 (1.4%) | 2137 (4.5%) | 4738 (8.6%) | 6849 (12.0%) | 9677 (15.3%) | 6535 (16.0%) | 1536 (12.8%) | 136 (8.9%) |
| In a cohabiting relationship | 15388 (4.5%) | 1318 (2.0%) | 2861 (6.1%) | 3170 (5.7%) | 3062 (5.3%) | 3022 (4.8%) | 1576 (3.9%) | 345 (2.9%) | 34 (2.2%) |
| In a relationship | 32066 (9.4%) | 12729 (19.7%) | 7347 (15.5%) | 3650 (6.6%) | 3146 (5.5%) | 3103 (4.9%) | 1669 (4.1%) | 390 (3.2%) | 32 (2.1%) |
| Married/Civil Partnership | 145166 (42.5%) | 2022 (3.1%) | 14235 (30.1%) | 31501 (57.0%) | 33622 (58.7%) | 35037 (55.5%) | 22295 (54.5%) | 5897 (49.0%) | 557 (36.3%) |
| Other | 2313 (0.7%) | 803 (1.2%) | 470 (1.0%) | 439 (0.8%) | 339 (0.6%) | 208 (0.3%) | 46 (0.1%) | 5 (0.0%) | 3 (0.2%) |
| Single (never married or in a civil partnership) | 85117 (24.9%) | 42004 (65.0%) | 18279 (38.7%) | 9084 (16.4%) | 6653 (11.6%) | 5955 (9.4%) | 2583 (6.3%) | 508 (4.2%) | 51 (3.3%) |
| Widowed | 14744 (4.3%) | 139 (0.2%) | 158 (0.3%) | 557 (1.0%) | 1490 (2.6%) | 3860 (6.1%) | 4895 (12.0%) | 2984 (24.8%) | 661 (43.0%) |
| Missing | 14678 (4.3%) | 4757 (7.4%) | 1762 (3.7%) | 2102 (3.8%) | 2098 (3.7%) | 2251 (3.6%) | 1282 (3.1%) | 364 (3.0%) | 62 (4.0%) |
| Socialize Frequency |  |  |  |  |  |  |  |  |  |
| Rarely/Never | 86212 (25.2%) | 14926 (23.1%) | 14063 (29.8%) | 16429 (29.7%) | 16052 (28.0%) | 15390 (24.4%) | 7446 (18.2%) | 1683 (14.0%) | 223 (14.5%) |
| 1-3 times a month | 79457 (23.2%) | 13115 (20.3%) | 11989 (25.4%) | 12973 (23.5%) | 13545 (23.7%) | 15310 (24.3%) | 9591 (23.5%) | 2655 (22.1%) | 279 (18.2%) |
| Once a week | 63389 (18.5%) | 11242 (17.4%) | 8055 (17.0%) | 9235 (16.7%) | 9847 (17.2%) | 12275 (19.4%) | 9352 (22.9%) | 3019 (25.1%) | 364 (23.7%) |
| Several days a week | 112898 (33.0%) | 25365 (39.2%) | 13142 (27.8%) | 16604 (30.1%) | 17815 (31.1%) | 20138 (31.9%) | 14492 (35.4%) | 4672 (38.8%) | 670 (43.6%) |
| Adequate Sleep Frequency |  |  |  |  |  |  |  |  |  |
| Hardly ever | 42262 (12.4%) | 10071 (15.6%) | 6175 (13.1%) | 7270 (13.2%) | 7113 (12.4%) | 7180 (11.4%) | 3498 (8.6%) | 836 (6.9%) | 119 (7.7%) |
| Some of the time | 117966 (34.5%) | 25492 (39.4%) | 18234 (38.6%) | 21289 (38.5%) | 20129 (35.2%) | 19465 (30.8%) | 10499 (25.7%) | 2569 (21.4%) | 289 (18.8%) |
| Most of the time | 140096 (41.0%) | 22792 (35.3%) | 17866 (37.8%) | 21383 (38.7%) | 23592 (41.2%) | 27803 (44.1%) | 19799 (48.4%) | 6106 (50.8%) | 755 (49.2%) |
| All of the time | 41632 (12.2%) | 6293 (9.7%) | 4974 (10.5%) | 5299 (9.6%) | 6425 (11.2%) | 8665 (13.7%) | 7085 (17.3%) | 2518 (20.9%) | 373 (24.3%) |
| Medical Diagnosis |  |  |  |  |  |  |  |  |  |
| No | 280712 (82.1%) | 54877 (84.9%) | 40813 (86.4%) | 47336 (85.7%) | 47419 (82.8%) | 49690 (78.7%) | 31090 (76.1%) | 8488 (70.6%) | 999 (65.0%) |
| Yes | 53164 (15.5%) | 7584 (11.7%) | 5438 (11.5%) | 6702 (12.1%) | 8628 (15.1%) | 12133 (19.2%) | 8917 (21.8%) | 3286 (27.3%) | 476 (31.0%) |
| Missing | 8080 (2.4%) | 2187 (3.4%) | 998 (2.1%) | 1203 (2.2%) | 1212 (2.1%) | 1290 (2.0%) | 874 (2.1%) | 255 (2.1%) | 61 (4.0%) |
| Mental Health Treatment in Past Year |  |  |  |  |  |  |  |  |  |
| No | 287518 (84.1%) | 51770 (80.1%) | 38632 (81.8%) | 46434 (84.1%) | 48454 (84.6%) | 53656 (85.0%) | 36239 (88.6%) | 10916 (90.7%) | 1417 (92.3%) |
| Yes | 50606 (14.8%) | 12028 (18.6%) | 8183 (17.3%) | 8221 (14.9%) | 8181 (14.3%) | 8732 (13.8%) | 4192 (10.3%) | 979 (8.1%) | 90 (5.9%) |
| Missing | 3832 (1.1%) | 850 (1.3%) | 434 (0.9%) | 586 (1.1%) | 624 (1.1%) | 725 (1.1%) | 450 (1.1%) | 134 (1.1%) | 29 (1.9%) |
| Experienced Childhood Trauma |  |  |  |  |  |  |  |  |  |
| No | 131004 (38.3%) | 16518 (25.6%) | 15289 (32.4%) | 21660 (39.2%) | 24223 (42.3%) | 27401 (43.4%) | 19235 (47.1%) | 5958 (49.5%) | 720 (46.9%) |
| Yes | 210952 (61.7%) | 48130 (74.4%) | 31960 (67.6%) | 33581 (60.8%) | 33036 (57.7%) | 35712 (56.6%) | 21646 (52.9%) | 6071 (50.5%) | 816 (53.1%) |
| Experienced Adult Trauma |  |  |  |  |  |  |  |  |  |
| No | 89087 (26.1%) | 17408 (26.9%) | 12573 (26.6%) | 16663 (30.2%) | 15786 (27.6%) | 15432 (24.5%) | 9027 (22.1%) | 1999 (16.6%) | 199 (13.0%) |
| Yes | 252869 (73.9%) | 47240 (73.1%) | 34676 (73.4%) | 38578 (69.8%) | 41473 (72.4%) | 47681 (75.5%) | 31854 (77.9%) | 10030 (83.4%) | 1337 (87.0%) |
| Physical Activity |  |  |  |  |  |  |  |  |  |
| Inactive | 135525 (39.6%) | 27949 (43.2%) | 23082 (48.9%) | 27178 (49.2%) | 24080 (42.1%) | 20054 (31.8%) | 9828 (24.0%) | 2883 (24.0%) | 471 (30.7%) |
| Active | 206431 (60.4%) | 36699 (56.8%) | 24167 (51.1%) | 28063 (50.8%) | 33179 (57.9%) | 43059 (68.2%) | 31053 (76.0%) | 9146 (76.0%) | 1065 (69.3%) |
| MHQ |  |  |  |  |  |  |  |  |  |
| Mean (SD) | 67.9 (72.7) | 21.2 (69.6) | 45.4 (69.2) | 64.6 (68.4) | 80.2 (67.6) | 92.6 (65.5) | 103 (59.7) | 111 (55.1) | 111 (63.7) |
| Median [Min, Max] | 79.1 [-166, 200] | 2.10 [-166, 200] | 45.2 [-166, 200] | 72.6 [-166, 200] | 93.5 [-166, 200] | 108 [-166, 200] | 117 [-166, 200] | 124 [-166, 200] | 125 [-166, 200] |
| Core Cognition |  |  |  |  |  |  |  |  |  |
| Mean (SD) | 81.4 (67.0) | 39.5 (63.2) | 61.0 (64.7) | 78.6 (64.7) | 92.3 (63.0) | 104 (60.4) | 113 (54.7) | 119 (51.3) | 116 (58.3) |
| Median [Min, Max] | 93.5 [-100, 200] | 25.4 [-100, 200] | 63.3 [-100, 200] | 88.8 [-100, 200] | 106 [-100, 200] | 118 [-100, 200] | 125 [-100, 200] | 130 [-100, 200] | 130 [-100, 200] |
| Adaptability and Resilience |  |  |  |  |  |  |  |  |  |
| Mean (SD) | 89.8 (67.4) | 50.7 (67.5) | 70.6 (66.7) | 88.3 (64.6) | 101 (62.7) | 110 (61.3) | 118 (55.2) | 125 (49.7) | 123 (55.4) |
| Median [Min, Max] | 105 [-100, 200] | 53.7 [-100, 200] | 81.7 [-100, 200] | 102 [-100, 200] | 116 [-100, 200] | 124 [-100, 200] | 132 [-100, 200] | 137 [-100, 200] | 134 [-100, 200] |
| Drive and Motivation |  |  |  |  |  |  |  |  |  |
| Mean (SD) | 83.4 (66.6) | 43.5 (64.7) | 62.6 (65.2) | 80.4 (63.9) | 94.3 (62.4) | 105 (60.1) | 114 (53.8) | 118 (49.7) | 114 (57.1) |
| Median [Min, Max] | 94.3 [-100, 200] | 36.8 [-100, 200] | 66.7 [-100, 200] | 89.7 [-100, 200] | 106 [-100, 200] | 120 [-100, 200] | 126 [-100, 200] | 129 [-100, 200] | 124 [-100, 200] |
| Mood and Outlook |  |  |  |  |  |  |  |  |  |
| Mean (SD) | 67.2 (71.1) | 24.4 (64.8) | 44.1 (66.3) | 62.0 (67.1) | 78.1 (67.6) | 91.2 (66.2) | 102 (61.5) | 111 (57.2) | 114 (61.7) |
| Median [Min, Max] | 73.7 [-100, 200] | -1.30 [-100, 200] | 35.6 [-100, 200] | 65.4 [-100, 200] | 88.8 [-100, 200] | 105 [-100, 200] | 116 [-100, 200] | 124 [-100, 200] | 129 [-100, 200] |
| Social Self |  |  |  |  |  |  |  |  |  |
| Mean (SD) | 70.7 (76.6) | 23.1 (69.5) | 50.2 (72.5) | 69.7 (72.8) | 83.5 (72.8) | 94.3 (71.8) | 103 (68.2) | 112 (64.6) | 116 (67.3) |
| Median [Min, Max] | 83.9 [-100, 200] | -3.40 [-100, 200] | 46.8 [-100, 200] | 80.6 [-100, 200] | 101 [-100, 200] | 115 [-100, 200] | 123 [-100, 200] | 131 [-100, 200] | 134 [-100, 200] |
| Mind-Body |  |  |  |  |  |  |  |  |  |
| Mean (SD) | 73.4 (64.7) | 44.6 (64.3) | 57.7 (63.8) | 68.7 (63.8) | 80.5 (62.9) | 90.1 (60.8) | 98.5 (55.5) | 102 (52.0) | 99.3 (57.0) |
| Median [Min, Max] | 84.1 [-100, 200] | 45.5 [-100, 200] | 64.5 [-100, 200] | 78.6 [-100, 200] | 92.7 [-100, 200] | 102 [-100, 200] | 109 [-100, 200] | 111 [-100, 200] | 108 [-100, 200] |

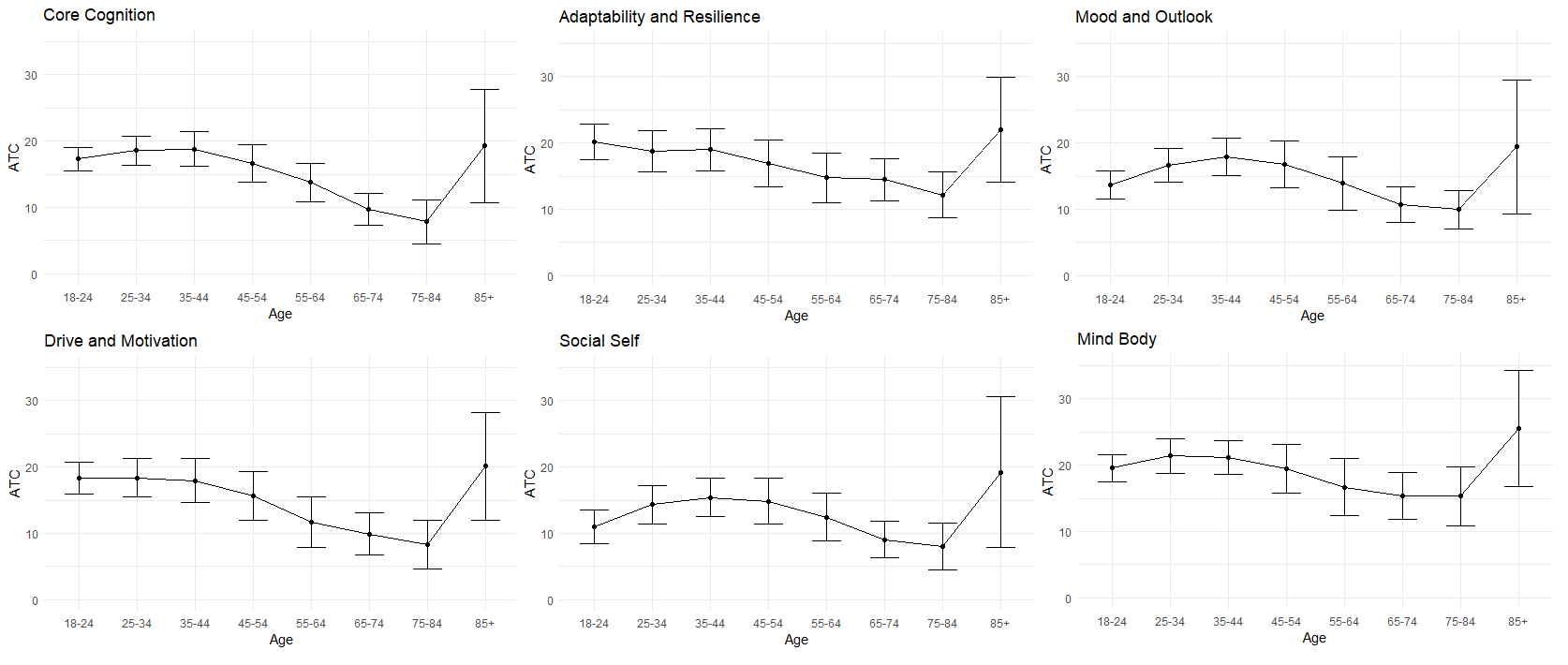
**Table 3. Sensitivity analysis. Reported ATC effects and standard errors on MHQ**

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| MHQ | GBM | Doubly Robust GBM | MI + GBM | Doubly Robust MI + GBM | MI + CBPS | Doubly Robust MI + CBPS |
| ATC | 17.86 | 17.74 | 17.75 | 17.77 | 18.15 | 17.87 |
| SE | 1.43 | 0.99 | 0.28 | 0.23 | 0.28 | 0.22 |
| SMD | 0.25 | 0.25 | 0.25 | 0.25 | 0.26 | 0.25 |

Chart, line chart

Description automatically generated

**Figure 1.** ATC’s of physical activity on overall MHQ scores across age groups. Error bars represent 95% CIs.



**Figure 2.** ATC’s of physical activity on subcategories of the MHQ across age groups. Error bars represent 95% CIs.

Chart, line chart

Description automatically generated

**Figure 3.** Marginal effects on MHQ by age for inactive and active groups with 95% CIs.

Graphical user interface, chart

Description automatically generated

**Figure 4.** Marginal effects on subcategories by age for inactive and active groups with 95% CIs.Levels of subcategory scores ranged from -100 to +200.