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Relationships of Cognitive Function With Subsequent Device-Measured Physical Activity and Sedentary Time in Healthy Individuals and Those With Bipolar Disorder: Findings From the UK Biobank

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ABSTRACT

Background: In bipolar disorder (BD), physical inactivity and sedentary behaviour are prevalent and have been linked to BD's cognitive symptoms, although the directionality of these links is not clear. This proof-of-concept study examined whether cognitive function during mid- and later-life was prospectively related to physical activity and sedentary time, and whether the association differed in presence or extent between those with BD and healthy controls.

Methods: Relevant UK Biobank data were available for 646 BD participants and 18,041 psychiatrically healthy controls, aged 40–69 years at baseline. Cognition was assessed during a baseline assessment, and wrist-worn accelerometry data were collected at a follow-up assessment 2.8–6.6 years later. Regression analyses examined prospective relationships of global cognition, diagnostic group, and their interaction, with physical activity (total, light, and moderate to vigorous) and sedentary time.

Results: Baseline cognitive function was inversely associated with light physical activity (coeff. = −5.64, 95% CI: −6.30 to −4.98) and positively associated with sedentary time (coeff. = 5.17, 95% CI: 4.48–5.86) and moderate-to-vigorous physical activity (coeff. = 0.48, 95% CI: 0.28–0.68) at follow-up. Observed effect sizes were small but significant. In general, associations were not moderated by age or diagnostic group.

Conclusions: The current study provides preliminary evidence that cognitive function may influence subsequent physical activity and sedentary time similarly in those with BD and healthy controls; however, further research is needed to confirm and further explore this findings.

Summary

- Significant outcomes
  - Baseline cognitive performance was associated with increased levels of moderate to vigorous physical activity and sedentary time, and decreased levels of light physical activity, at a follow-up 2.8–6.6 years later.
  - The association of cognitive function with both physical activity and sedentary time was overall not moderated by diagnostic group or age.
- Limitations
  - A composite cognitive score was used to provide greater measurement validity; however, it is likely certain cognitive domains are more relevant to physical activity and sedentary behaviour than others.
  - Confounding factors that are known to cause fluctuations in physical activity and time spent being sedentary over prolonged periods, such as mood state and recent life events, were not collected in the dataset.
  - Accelerometry data were not collected on more than one occasion or at the same time as the cognitive assessment.

1 | Introduction

Bipolar disorder (BD) is associated with low levels of physical activity and its more structured form, exercise, as well as with higher amounts of sedentary time, even when euthymic, resulting in those with BD often not meeting recommended physical activity guidelines [1, 2]. Impairments in cognitive function are also apparent for more than 50% of those with BD, affecting various cognitive domains, as well as cognition globally, during symptomatic and asymptomatic states [3, 4]. Existing general population research has largely linked increased physical activity and reduced sedentary time to better cognition [5–8], however research on these links in BD is sparse and the directionality inconsistent [9–13]. Indeed, recent work from our group has shown a *negative* association in which high levels of self-reported physical activity (in comparison to low–moderate levels) were associated with a lower global cognitive score in BD [9, 13], while other BD studies have found positive associations [10, 14], and in a separate study failed to observe any associations [12].

The temporal directionality of the associations between physical inactivity or sedentariness and cognitive impairment is not clear, as most observational studies on the topic in those with and without BD have been conducted using cross-sectional designs. Despite this, there is often an implicit assumption that cognitive impairment is the *consequence* of physical inactivity and a sedentary lifestyle, leading to assertions that interventions targeting a more active lifestyle will improve cognition in both the general population and in BD populations specifically [6, 15]. A recent umbrella review, however, of 24 meta-analyses of interventional studies reported only small exercise-related benefits on cognition that became almost negligible after accounting for key moderators and correcting for publication bias [16]. It is plausible that these weak intervention effects were because baseline cognitive functioning impacts physical activity levels or sedentary behaviour [17–20] more than physical activity levels and/or sedentary behaviour affecting cognition.

Cognition can be bidirectionally associated with motivation and reward processing, which are important for the adoption and maintenance of physical activity [21]. Motivation may be negatively influenced by executive control and planning difficulties [22], which are necessary for self-evaluation, monitoring, and self-reinforcement (components of self-regulation) [23]. Thus, it is plausible that individual differences in cognitive function indirectly influence the extent of later physical activity and sedentary behaviour, though evidence that motivational and reward processes change across the lifespan suggests that the nature of this influence may vary as a function of age [24–26]. This may be particularly relevant to the 'later-life' period (e.g., ~60 years and above) in which mental processes are known to deteriorate, and physical activity becomes less intense and less regular [27–29].

In BD, in addition to widely recognised impairments in executive function, motivation and reward processing are also known to be dysregulated [30–32]. Thus, the influence of cognition on physical activity and sedentariness may be even more pronounced in this group than that of the general population. However, the extent to which cognition may predict later levels of physical activity or sedentary behaviour in BD, or in those without, is largely unknown. Evidence on whether different types of physical activity may be differently influenced by cognition is also lacking, although intuitively it seems likely that impairments in motivation and reward processing (and thus cognition generally) would particularly impact more vigorous or intentional types of physical activity, such as exercise, compared to impacting more incidental lighter types of activity, such as walking.

There is considerable potential to address the paucity of research on cognition and physical activity and sedentary behaviour in BD using the UK Biobank dataset [33]. This dataset is a unique resource with baseline cognitive data available for a large sample of those with BD and psychiatrically healthy controls, as well as objective measurements of physical activity and sedentary time available for a sub-sample of participants at a follow-up timepoint (2.8–6.6 years later).

1.1 | Aims of the Study

In this proof-of-concept study, we used the UK Biobank dataset to specifically examine whether cognitive function was prospectively associated with later levels of physical activity and sedentary time, and whether these associations differed in presence or extent between those with and without BD. We also examined whether these associations differed according to age, as well as different forms of physical activity, namely light physical activity (e.g., walking and/or habitual activities) compared with moderate-to-vigorous physical activity (MVPA) (e.g., cycling, running).

2 | Materials and Methods

We accessed the UK Biobank; a prospective dataset of approximately 500,000 participants, aged 40–69 at baseline. Data across a wide range of lifestyle, health, demographic,

cognitive, and biological variables were collected across 22 centres throughout the UK, with baseline assessments conducted between February 2005 and October 2010. This included the collection of three cognitive tests. An additional cognitive test was added to the existing protocol in the final 2 years of the assessment period (2009–2010). We included this cognitive test in the current study, and thus only sampled baseline data collected between 2009 and 2010. Device-measured physical activity and sedentary time data were collected at a subsequent timepoint (2.8–6.6 years later) from a subset of some 100,000 participants between June 2013 and December 2015 (refer to Figure 1 for visualisation of the data collection timeline). *No other data* (including cognitive data) were collected at this same timepoint. Full details of the data collection procedures are provided elsewhere [33]. The UK Biobank has approval from the Northwest Multi-Centre Research Ethics committee (reference 16/NW/0274 and 11/NW/0382), and all participants gave written informed consent.

2.1 | Diagnostic Criteria for Participants and Healthy Controls

BD status was determined using a combination of self-report data and hospital records. Participants were classified as having BD if: (1) they matched ICD-10 diagnostic codes for BD, (2) they self-reported having BD, mania, or manic depression during an interview with a trained nurse, (3) they fulfilled criteria for having BD based on the mood disorder questionnaire given at baseline, or (4) they fulfilled criteria for having BD based on the online mental health questionnaire completed between 2016 and 2017. The full methodology of categorising participants based on the baseline mood disorder questionnaire is detailed in a previous study that assessed the prevalence of mood disorders in the cohort [34]. In brief, the study used a touchscreen questionnaire based on symptoms within the Structured Clinical Interview for DSM-IV axis I disorders (introduced in the final 2 years of recruitment; subsample of ~120,000 participants) to identify participants as likely having BD type I or type II, major depressive disorder, or no indicated mental disorder. This categorisation was validated against other demographic and clinical information available in the dataset. Participants who completed the online mental health questionnaire (subsample of ~100,000 participants) were categorised as having lifetime bipolar disorder if they reported a period of feeling high, hyper, excited, or intense irritability that lasted at least 1 week and was associated with at least four manifestations of mania (for full details see Davis et al. [35]).

Participants were classified as healthy controls if they did not meet any of the above criteria, did not have any other mental disorder (as determined by ICD-10, self-report, and baseline and online mental health questionnaire classifications), and were not using any type of psychotropic medication. If participants met any of these criteria, they were excluded from the study. Participants who were pregnant, as well as those with neurological conditions known to affect cognitive functioning were also excluded from both the BD and psychiatrically healthy control groups (see Supporting Information Appendix S1 for a detailed list).

2.2 | Baseline

2.2.1 | Cognitive Assessment

Cognitive functioning was assessed through a brief computerised battery (15 min) obtained at baseline, which was developed specifically for the UK Biobank and designed to be completed electronically without examiner supervision. Assessments were completed at the UK Biobank assessment centres and included measurement of the following cognitive domains: visuospatial memory, processing speed, reasoning, and prospective memory.[1] In the current study, scores were coded so that higher scores equated to better performance. A global cognitive score was then created by: (1) calculating *z*-scores for the continuous measures (visuospatial

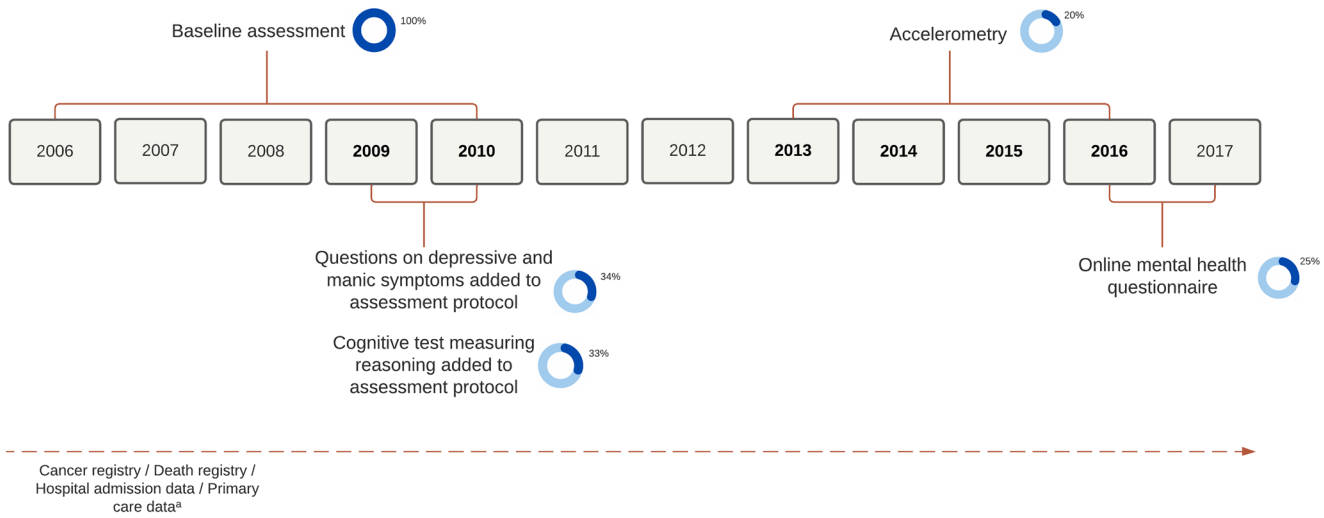

FIGURE 1 | Timeline of UK Biobank data relevant to the current study. Data included in this study come from the bolded years. The shaded section in the charts represents the percentage of the full UK Biobank cohort that were included in the respective components of data collection. There are several other follow up components that are not depicted here. In figure superscript "a" represents data collection related to medical records is ongoing.

memory, processing speed, and reasoning) based on means and standard deviations in the full sample, and (2) summing these z-scores with the raw prospective memory score (dichotomous variable equalling 0 or 1), as has been done previously [36]. A global cognitive score was used rather than individual domain scores, as aggregate scores are known to have greater validity in measuring the construct of interest and are more reliable [37].

2.2.2 | Baseline Covariates

Age and sex were collected at baseline, and socio-economic status (SES) measured by the Townsend Deprivation Index [38] at recruitment.

2.3 | Follow-Up (2.8–6.6 Years Later)

2.3.1 | Device-Measured Physical Activity and Sedentary Time

At follow-up, physical activity was measured over a 7-day period using an Axivity wrist-worn AX3 triaxial accelerometer, worn on the dominant hand continuously for 7 days. The raw accelerometer data were calibrated, and wear-time periods were calculated using the UK Biobank pre-processing measures [39]. The average proportion of time spent being sedentary and in light physical activity, MVPA and sleep per hour across all days were calculated using a machine learning method by Walmsley et al. [40]. Hourly values were summed to create average hours *per day* of each behaviour (light physical activity, MVPA, sedentary time and sleep; refer to Supporting Information S1 for details on behaviour classification), and then converted to minutes per day for interpretability. Light physical activity and MVPA were summed to reflect total physical activity per day. In line with data quality metrics from the UK Biobank, participants were excluded from the analyses if (i) their accelerometer record failed calibration, including those not calibrated on their own data, (ii) they had less than 3 days of valid wear time, or if they did not have data in each 1-h period of the 24 h cycle, (iii) the average acceleration was implausibly high (> 100 mg) or (iv) more than 1% of readings fell outside the device's dynamic range of ±8 g before or after calibration [39, 40].

2.3.2 | Follow-Up Covariates

Average minutes of sleep per day, as well as the season when accelerometry data were collected, were used as a covariate in the statistical models.

2.4 | Statistical Analysis

All analyses were completed using the Statistical Package for the Social Sciences (SPSS) Version 29 (IBM). Demographic, cognitive, and accelerometry data of each diagnostic group were compared using χ^2 tests and one-way ANOVAs, and associations of the different types of activity assessed using partial correlations controlling for age, sex, baseline SES, season of accelerometry data collection, and average minutes of sleep per day at follow-up.

To assess whether cognitive function was prospectively associated with later physical activity and sedentary time and whether this relationship was moderated by diagnostic group membership, two separate moderation models were run (Model 1 of the PROCESS plugin for SPSS (v4.2)), with either physical activity or sedentary time at follow-up as the dependent variable (Y), global cognition at baseline set as the independent variable (X), and diagnostic group membership as the moderator (W). Age, sex, baseline SES, average minutes of sleep per day at follow-up, season when accelerometry data was collected, and months between baseline and follow-up were entered as covariates in all models a priori.

To explore whether the association between cognition and physical activity was influenced by the *type of physical activity*, two secondary moderation models were run with either light physical activity or MVPA specified as the dependent variable (Y). In the models in which light physical activity or MVPA was not entered as the dependent variable, they were entered as a covariate a priori. All other variables in the models remained the same.

Lastly, to explore whether these relationships changed with age, participants were stratified by grouping those aged 40–59 at baseline into a 'mid-life' category and those aged 60 or above at baseline into a 'later-life' category. We then re-ran the above-mentioned models in the age-stratified groups. Total physical activity was not considered in these models because both light physical activity and MVPA were found to be significantly related to cognition in the full sample models described above. Sex, baseline SES, average minutes of sleep per day at follow-up, season when accelerometry data was collected, and months between baseline and follow-up were entered as covariates in all models a priori. A false discovery rate of $p < 0.05$ was applied to all results to account for multiple comparisons using the Benjamini-Hochberg method.

3 | Results

3.1 | Participants Included in the Analyses, Demographic Group Comparisons, and Activity Correlations

The final sample included 18,687 participants, of whom 646 met UK Biobank criteria for BD and 18,041 were psychiatrically healthy controls (see Figure S1 for more detail on participant sampling, including exclusion counts). Demographic characteristics and mean cognitive and accelerometry scores of the diagnostic groups are compared in Table 1. The BD cohort had a greater proportion of females and were, on average, significantly younger and of lower SES in comparison to the controls. Additionally, those with BD had *more* minutes sleep, and *fewer* minutes of total physical activity and MVPA in comparison to controls.

Correlations between the different types of activity indicated that sedentary time was negatively correlated with both light physical activity (very strongly) and MVPA (weakly) in the full sample, as well as in the diagnostic and age-stratified subgroups. However, light physical activity and MVPA did not significantly correlate with each other, with the exception of being weakly

TABLE 1 | Characteristics of participants with bipolar disorder and healthy controls.

Characteristic	BD ($n=646$)	HC ($n=18,041$)	Statistical comparison	Effect size[a]
Age[b]	54.75 ± 8.03	57.08 ± 7.88	$F(1,18,685)=54.52$, $p<0.001$*	−0.30
Sex (% female)[b]	56.7	52.0	$\chi^2=6.58$, $p=0.010$*	−0.01
Townsend deprivation index[b]	−0.84 ± 2.93	−1.66 ± 2.63	$F(1,18,685)=60.22$, $p<0.001$*	0.30
Global cognitive score[b]	0.76 ± 2.12	0.84 ± 2.07	$F(1,18,685)=0.82$, $p=0.365$	−0.04
Total physical activity (minutes per day)[c]	338.77 ± 109.97	347.72 ± 100.86	$F(1,18,685)=4.88$, $p=0.027$*	−0.08
Light physical activity (minutes per day)[c]	301.45 ± 103.71	307.68 ± 97.48	$F(1,18,685)=2.54$, $p=0.111$	−0.06
Moderate-to-vigorous physical activity (minutes per day)[c]	37.32 ± 28.74	40.03 ± 27.77	$F(1,18,685)=5.92$, $p=0.015$*	−0.07
Sedentary time (minutes per day)[c]	565.14 ± 112.40	563.67 ± 106.50	$F(1,18,685)=0.18$, $p=0.732$	0.01
Sleep (minutes per day)[c]	535.91 ± 81.06	528.55 ± 72.60	$F(1,18,685)=6.36$, $p=0.012$*	0.10
Season of accelerometry assessment (% winter/autumn/spring/summer)[c]	21.5/30.8/24.4/23.3	21.7/29.7/22.9/25.7	$\chi^2=3.27$, $p=0.352$	0.01
Months between timepoint 1 and timepoint 2	56.52 ± 8.49	56.89 ± 8.72	$F(1,18,685)=1.08$, $p=0.298$	−0.04

Abbreviations: BD, bipolar disorder; HC, healthy control.
[a]Cohen's *d* effect size is reported for continuous variables, ϕ for categorical variables with two groups, and Cramer's *V* for categorical variables with > 2 groups. Data are expressed as mean ± SD.
[b]Data collected at baseline assessment.
[c]Data collected at follow-up assessment.

positively associated in the later-life (≥ 60 years of age at baseline) group. All relevant correlation coefficients can be found in the Supporting Information (Tables S1–S5).

3.2 | Total Physical Activity and Sedentary Time

Results of the primary models are reported in Table 2, with full model output (including covariates) shown in Table S6. In all participants, better cognitive performance at baseline was inversely associated with total physical activity and greater sedentary time at follow-up, with 5.2 min/day less total physical activity and 5.2 min/day more sedentary time for every one-unit increase in the global cognitive score. These associations were not significantly moderated by diagnostic group, nor was there a main effect of diagnostic group for either total physical activity or sedentary time.

3.3 | Light Physical Activity and MVPA

Results of the secondary models exploring subtypes of physical activity are reported in Table 2, with full model output (including covariates) shown in Table S7. Cognitive performance at baseline was inversely associated with levels of light physical activity and positively associated with MVPA at follow-up. Light physical activity was 5.6 min/day less, and MVPA 0.5 of a minute per day more, for every one unit increase in the global cognitive score. These associations were not significantly moderated by diagnostic group, nor was there a main effect of diagnostic group for either light physical activity or MVPA.

3.4 | Age-Stratified Models

3.4.1 | Midlife

Results of the midlife model are reported in Table 3, with full model output (including covariates) shown in Table S8. In mid-life participants (40–59 years of age at baseline), global cognition was inversely associated with light physical activity (7.3 min/day decrease) and positively associated with both sedentary time (6.7 min/day increase) and MVPA (0.6 of a minute per day increase). These associations were not moderated by diagnostic group membership, nor were there any main effects of diagnostic group.

3.4.2 | Later-Life

Results of the later-life model are reported in Table 4, with full model output (including covariates) shown in Table S9.

TABLE 2 | Associations of global cognition, diagnostic group, and their interaction with device-measured physical activity and sedentary time.

	Coeff.[a]	SE	*p*	95% LLCI[b]	95% ULCI[c]
Global cognition					
Total physical activity	−5.16	0.35	**<0.0001***	−5.85	−4.47
Light physical activity	−5.64	0.34	**<0.0001***	−6.30	−4.98
Moderate to vigorous physical activity	0.48	0.10	**<0.0001***	0.28	0.68
Sedentary time	5.17	0.35	**<0.0001***	4.48	5.86
Diagnostic group					
Total physical activity	−8.18	3.77	0.0301*	−15.58	−0.79
Light physical activity	−5.43	3.60	0.1320	−12.49	1.63
Moderate to vigorous physical activity	−2.61	1.09	0.0164*	−4.47	−0.48
Sedentary time	8.06	3.77	0.0327*	0.66	15.45
Global cognition *by* diagnostic group interaction					
Total physical activity	−2.98	1.78	0.0938	−6.46	0.51
Light physical activity	−2.25	1.70	0.1851	−5.57	1.08
Moderate to vigorous physical activity	−0.68	0.51	0.1867	−1.68	0.33
Sedentary time	3.02	1.78	0.0894	−0.46	6.50

Note: A * indicates significance at $p < 0.05$ *before* Benjamini-Hochberg FDR correction for multiple comparisons, and bolded values indicate significance *after* Benjamini-Hochberg FDR correction for multiple comparisons. Healthy control coded as 0, BD coded as 1. The full primary and secondary models, including covariates, are reported in Tables S6 and S7 for brevity.
[a]Unstandardised regression coefficient.
[b]Lower-limit confidence interval.
[c]Upper-limit confidence interval.

TABLE 3 | Age stratified associations (< 60 years of age at timepoint 1).

	Coeff.[a]	SE	*p*	95% LLCI[b]	95% ULCI[c]
Global cognition					
Light physical activity	−7.28	0.49	**<0.0001***	−8.23	−6.33
Moderate to vigorous physical activity	0.63	0.14	**<0.0001***	0.35	0.91
Sedentary time	6.67	0.50	**<0.0001***	5.68	7.66
Diagnostic group					
Light physical activity	−7.75	4.68	0.0976	−16.91	1.42
Moderate to vigorous physical activity	−3.18	1.37	0.0204*	−5.86	−0.49
Sedentary time	10.57	4.86	0.0295*	1.05	20.09
Global cognition *by* diagnostic group interaction					
Light physical activity	−0.66	2.34	0.7778	−5.26	3.93
Moderate to vigorous physical activity	−0.64	0.69	0.3504	−1.99	0.71
Sedentary time	1.34	2.44	0.5829	−3.44	6.11

Note: A * indicates significance at $p < 0.05$ *before* Benjamini-Hochberg FDR correction for multiple comparisons, and bolded values indicate significance *after* Benjamini-Hochberg FDR correction for multiple comparisons. Healthy control coded as 0, BD coded as 1. The full model, including covariates, is reported in Table S8 for brevity.
[a]Unstandardised regression coefficient.
[b]Lower-limit confidence interval.
[c]Upper-limit confidence interval.

In later-life participants (≥60 years of age at baseline), global cognition was inversely associated with light physical activity (3.8 min/day decrease) and positively associated with sedentary time (3.3 min/day increase). Global cognition was also positively associated with MVPA (0.4 of a minute increase per day). These associations were not moderated by diagnostic group, nor were there any diagnostic group main effects.

4 | Discussion

This study used UK Biobank data to explore whether global cognitive functioning was prospectively associated with later physical activity and sedentary time in mid-and later-life participants with BD and psychiatrically healthy controls. We found that higher global cognitive performance in the sample at baseline was prospectively associated with less light physical activity (e.g., walking and/or habitual activities) and greater sedentary time, as well as greater MVPA. The absence of interaction effects with diagnostic group suggests that the nature of these associations is similar in people with BD and healthy controls. These associations also did not appear to be moderated by age, since they were present and in the same direction in both mid-life and later-life participants, albeit being slightly stronger in the former. However, it should be noted that the magnitude of all associations was small despite being statistically significant.

Regarding directionality, the positive association between global cognition and MVPA in the full sample in this study is in line with several general population studies that have focused on total activity levels [17–20]. Although our study is the first to have looked at subtypes of physical activity (both in BD and more generally) in this context, it is unsurprising that MVPA was marginally increased in those with higher cognitive function since structured exercise and/or participation in sports are large contributors to MVPA levels [41]. These are *intentional* forms of physical activity that we speculate are *more likely* to be affected by cognitive processes involved in motivation and effort. This contrast with light physical activity and sedentariness, which tend to involve activities such as housework and/or occupational office work, where participation is less affected by cognitive processes involved in motivation and effort as they are essential parts of daily life.

To this end, the negative directionality of associations between light physical activity and sedentary time might be explained as simply reflecting that participants with greater cognitive performance at baseline were more likely to be employed in occupations involving less daily physical movement and more sedentary time at the follow-up (i.e., office workers). Although detailed occupational information was not available in the UK Biobank to confirm this, past studies have found that cognitive ability is correlated with degree of educational achievement [42], which affects occupational choice. Higher cognitive ability has also been linked specifically to cognitively demanding professions in which office work is more common, such as law, science, research, and finance, consistent with this speculation. In contrast, lower cognitive ability has been linked to professions in which more physical activity is required, such as factory work or hairdressing [43]. While this assertion is purely speculative and needs to be explored further, it is relevant that in the current data there was a positive correlation ($r=0.92$, $p<0.001$) between global cognition and SES[2] (data not shown), which can be considered a proxy marker of occupational status [44]. It should be noted, however, that the SES measure was only available at baseline and not the timepoint at which the accelerometry data was collected.

Regarding effect size, the strength of associations in our study suggests that cognitive functioning is not a particularly

TABLE 4 | Age stratified associations (≥60 years of age at timepoint 1).

	Coeff.[a]	SE	*p*	95% LLCI[b]	95% ULCI[c]
Global cognition					
Light physical activity	−3.76	0.45	**<0.0001***	−4.65	−2.88
Moderate to vigorous physical activity	0.42	0.14	**0.0032***	0.14	0.70
Sedentary time	3.33	0.48	**<0.0001***	2.39	4.27
Diagnostic group					
Light physical activity	−1.66	5.76	0.7736	−12.94	9.63
Moderate to vigorous physical activity	−1.58	1.81	0.3851	−5.13	1.98
Sedentary time	3.60	6.11	0.5554	−8.37	15.58
Global cognition *by* diagnostic group interaction					
Light physical activity	−3.42	2.59	0.1870	−8.49	1.66
Moderate to vigorous physical activity	−0.59	0.82	0.4692	−2.19	1.01
Sedentary time	4.25	2.74	0.1223	−1.14	9.63

Note: A * indicates significance at $p<0.05$ *before* Benjamini-Hochberg FDR correction for multiple comparisons, and bolded values indicate significance *after* Benjamini-Hochberg FDR correction for multiple comparisons. Healthy control coded as 0, BD coded as 1. The full model, including covariates, is reported in Table S9 for brevity.

[a]Unstandardised regression coefficient.

[b]Lower-limit confidence interval.

[c]Upper-limit confidence interval.

meaningful predictor of future physical activity levels in people with BD and healthy controls. However, it is also important to note that the strength of these associations may be moderated by unspecified variables that we were unable to explore in the current study by nature of the methodological limitations of the UK Biobank. Indeed, confounding factors that are known to cause fluctuations in physical activity and time spent being sedentary over prolonged periods, such as mood state and recent life events [45, 46], were not collected in the dataset. Thus, we were unable to examine whether cognition was differently related to activity levels in participants with different mood states or life event burdens at follow-up. Similarly, sufficient data on other health risk behaviours, such as diet and sleep *quality*, were not comprehensively collected across the timepoints included, and as such not considered in the current study. Future research would do well to explore a more comprehensive grouping of health risk behaviours, given they are likely to co-occur in individuals with BD. Unfortunately, accelerometry data were also not collected on more than one occasion or at the same time as the cognitive assessment. Thus, we were also unable to longitudinally track the stability of physical activity levels nor the degree to which they correlated with cognition at different points in time, where differences in the latter might signal the influence of unmeasured time-varying confounding factors.

Another limitation of the study relates to our use of a composite cognitive score as the primary cognitive measure. Although this was used to provide greater measurement validity given the limited and non-BD specific cognitive measures available in the UK Biobank dataset, it remains likely that certain cognitive domains, such as executive functioning, attention, and memory, are more relevant to physical activity and sedentary behaviour than others due to their role in motivation [22] and reward processing [47]. To explore inter-relationships between cognition and physical activity levels more comprehensively in future, further studies should simultaneously track cognition and physical activity across multiple timepoints and use more complete cognitive assessments and cognitive domain focussed analyses. These studies should also incorporate explicit measures of reward processing and motivation to better understand their role in the association of cognition and physical activity/sedentariness.

5 | Conclusion

In summary, our findings, although preliminary, provide evidence of a positive association between baseline cognition and follow-up MVPA and sedentary time, while an inverse association was observed for light-intensity physical activity. Although effect sizes in our study were small, and several limitations were evident, the significant findings do warrant further prospective analyses. Determining the directionality of this association is particularly relevant for BD, as targeting cognition in this group may be an appropriate intervention to increase physical exercise, complementing the more widely accepted inverse. Not only would this be beneficial for cognitive outcomes in BD, but it could lead to positive flow-on effects relating to both mood and physical health commonly associated with increased exercise.

Author Contributions

E.R., T.E.V.R., and D.W.D. conceptualised the research idea; E.R. performed the statistical analysis and wrote the manuscript; all authors contributed to the interpretation of results and re-drafting of the manuscript.

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Conflicts of Interest

Roger S. McIntyre has received research grant support from CIHR/GACD/National Natural Science Foundation of China (NSFC) and the Milken Institute; speaker/consultation fees from Lundbeck, Janssen, Alkermes, Neumora Therapeutics, Boehringer Ingelheim, Sage, Biogen, Mitsubishi Tanabe, Purdue, Pfizer, Otsuka, Takeda, Neurocrine, Sunovion, Bausch Health, Axsome, Novo Nordisk, Kris, Sanofi, Eisai, Intra-Cellular, NewBridge Pharmaceuticals, Viatris, Abbvie, Atai Life Sciences. Dr. Roger McIntyre is the CEO of Braxia Scientific Corp.

Data Availability Statement

Data are not available to share. Only researchers with approved access to UK Biobank data may access the relevant data. Researchers can apply to UK Biobank directly at https://www.ukbiobank.ac.uk/enable-your-research/apply-for-access.

Peer Review

The peer review history for this article is available at https://www.webofscience.com/api/gateway/wos/peer-review/10.1111/acps.70011.

Endnotes

[1] Further detail on each measure can be found in the Supporting Information S1.

[2] For the purpose of this analysis, SES (as measured by the Townsend deprivation index) was coded so that a higher score equated to greater SES.

References

1. C. A. Janney, A. Fagiolini, H. A. Swartz, J. M. Jakicic, R. G. Holleman, and C. R. Richardson, "Are Adults With Bipolar Disorder Active? Objectively Measured Physical Activity and Sedentary Behavior Using Accelerometry," *Journal of Affective Disorders* 152–154, no. 1 (2014): 498–504, https://doi.org/10.1016/j.jad.2013.09.009.

2. D. Vancampfort, J. Firth, F. B. Schuch, et al., "Sedentary Behavior and Physical Activity Levels in People With Schizophrenia, Bipolar Disorder and Major Depressive Disorder: A Global Systematic Review and Meta-Analysis," *World Psychiatry* 16, no. 3 (2017): 308–315, https://doi.org/10.1002/wps.20458.

3. K. E. Burdick, J. F. Goldberg, and M. Harrow, "Neurocognitive Dysfunction and Psychosocial Outcome in Patients With Bipolar I Disorder

at 15 Year Follow-Up," *Acta Psychiatrica Scandinavica* 122, no. 6 (2010): 499–506, https://doi.org/10.1111/j.1600-0447.2010.01590.x.

4. T. E. Van Rheenen, K. E. Lewandowski, I. E. Bauer, et al., "Current Understandings of the Trajectory and Emerging Correlates of Cognitive Impairment in Bipolar Disorder: An Overview of Evidence," *Bipolar Disorders* 22, no. 1 (2020): 13–27, https://doi.org/10.1111/bdi.12821.

5. C. H. Hillman, K. I. Erickson, and A. F. Kramer, "Be Smart, Exercise Your Heart: Exercise Effects of Brain and Cognition," *Nature* 9 (2008): 58–65.

6. J. Bangsbo, J. Blackwell, C. J. Boraxbekk, et al., "Copenhagen Consensus Statement 2019: Physical Activity and Ageing," *British Journal of Sports Medicine* 53, no. 14 (2019): 856–858, https://doi.org/10.1136/bjsports-2018-100451.

7. R. S. Falck, J. C. Davis, and T. Liu-Ambrose, "What Is the Association Between Sedentary Behaviour and Cognitive Function? A Systematic Review," *British Journal of Sports Medicine* 51, no. 10 (2017): 800–811, https://doi.org/10.1136/bjsports-2015-095551.

8. O. Olanrewaju, S. Stockwell, B. Stubbs, and L. Smith, "Sedentary Behaviours, Cognitive Function, and Possible Mechanisms in Older Adults: A Systematic Review," *Aging Clinical and Experimental Research* 32, no. 6 (2020): 969–984, https://doi.org/10.1007/s40520-019-01457-3.

9. E. Ringin, D. W. Dunstan, R. S. McIntyre, et al., "Differential Associations of Mentally-Active and Passive Sedentary Behaviours and Physical Activity With Putative Cognitive Decline in Healthy Individuals and Those With Bipolar Disorder: Findings From the UK Biobank Cohort," *Mental Health and Physical Activity* 24 (2023): 100514, https://doi.org/10.1016/j.mhpa.2023.100514.

10. F. T. Fellendorf, N. Kainzbauer, M. Platzer, et al., "Gender Differences in the Association Between Physical Activity and Cognitive Function in Individuals With Bipolar Disorder," *Journal of Affective Disorders* 221 (2017): 232–237, https://doi.org/10.1016/j.jad.2017.06.048.

11. M. Aas, T. Ueland, R. H. Mørch, et al., "Physical Activity and Childhood Trauma Experiences in Patients With Schizophrenia or Bipolar Disorders," *World Journal of Biological Psychiatry* 22, no. 8 (2021): 637–645, https://doi.org/10.1080/15622975.2021.1907707.

12. J. L. Burgess, A. J. Bradley, K. N. Anderson, P. Gallagher, and R. H. McAllister-Williams, "The Relationship Between Physical Activity, BMI, Circadian Rhythm, and Sleep With Cognition in Bipolar Disorder," *Psychological Medicine* 52, no. 3 (2022): 467–475, https://doi.org/10.1017/S003329172000210X.

13. E. Ringin, D. W. Dunstan, D. Meyer, et al., "Relative Associations of Behavioral and Physiological Risks for Cardiometabolic Disease With Cognition in Bipolar Disorder During Mid and Later-Life: Findings From the UK Biobank," *Psychological Medicine* 54, no. 10 (2024): 1–11, https://doi.org/10.1017/S0033291724000722.

14. M. Aas, S. Djurovic, T. Ueland, et al., "The Relationship Between Physical Activity, Clinical and Cognitive Characteristics and BDNF mRNA Levels in Patients With Severe Mental Disorders," *World Journal of Biological Psychiatry* 20, no. 7 (2019): 567–576, https://doi.org/10.1080/15622975.2018.1557345.

15. A. Kucyi, M. T. Alsuwaidan, S. S. Liauw, S. Roger, and A. Kucyi, "Aerobic Physical Exercise as a Possible Treatment for Neurocognitive Dysfunction in Bipolar Disorder Aerobic Physical Exercise as a Possible Treatment for Neurocognitive Dysfunction in Bipolar Disorder," *Postgraduate Medicine* 122, no. 6 (2015): 107–116, https://doi.org/10.3810/pgm.2010.11.2228.

16. L. F. Ciria, R. Román-Caballero, M. A. Vadillo, et al., "An Umbrella Review of Randomized Control Trials on the Effects of Physical Exercise on Cognition," *Nature Human Behaviour* 7, no. 6 (2023): 928–941, https://doi.org/10.1038/s41562-023-01554-4.

17. B. Cheval, Z. Csajbók, T. Formánek, et al., "Association Between Physical-Activity Trajectories and Cognitive Decline in Adults 50 Years of Age or Older," *Epidemiology and Psychiatric Sciences* 30 (2021): 1–10, https://doi.org/10.1017/S2045796021000688.

18. B. Cheval, E. Tipura, N. Burra, et al., "Avoiding Sedentary Behaviors Requires More Cortical Resources Than Avoiding Physical Activity: An EEG Study," *Neuropsychologia* 119 (2018): 68–80, https://doi.org/10.1016/j.neuropsychologia.2018.07.029.

19. B. Cheval, D. Orsholits, S. Sieber, D. Courvoisier, S. Cullati, and M. P. Boisgontier, "Relationship Between Decline in Cognitive Resources and Physical Activity," *Health Psychology* 39, no. 6 (2020): 519–528, https://doi.org/10.1037/hea0000857.

20. Z. Csajbók, S. Sieber, S. Cullati, P. Cermakova, and B. Cheval, "Physical Activity Partly Mediates the Association Between Cognitive Function and Depressive Symptoms," *Translational Psychiatry* 12, no. 1 (2022): 414, https://doi.org/10.1038/s41398-022-02191-7.

21. M. M. Michaelsen and T. Esch, "Motivation and Reward Mechanisms in Health Behavior Change Processes," *Brain Research* 1757 (2021): 147309, https://doi.org/10.1016/j.brainres.2021.147309.

22. U. Arnautovska, J. P. Kesby, N. Korman, et al., "Biopsychology of Physical Activity in People With Schizophrenia: An Integrative Perspective on Barriers and Intervention Strategies," *Neuropsychiatric Disease and Treatment* 18 (2022): 2917–2926, https://doi.org/10.2147/NDT.S393775.

23. D. Kwasnicka, S. U. Dombrowski, M. White, and F. Sniehotta, "Theoretical Explanations for Maintenance of Behavior Change: A Systematic Review of Behavior Theories Theoretical Explanations for Maintenance of Behaviour Change: A Systematic Review of Behaviour Theories," *Health Psychology Review* 10, no. 3 (2016): 277–296.

24. T. M. Le, H. Chao, I. Levy, and C.-S. R. Li, "Age-Related Changes in the Neural Processes of Reward-Directed Action and Inhibition of Action," *Frontiers in Psychology* 11 (2020): 1121, https://doi.org/10.3389/fpsyg.2020.01121.

25. G. E. Ennis, T. M. Hess, and B. T. Smith, "The Impact of Age and Motivation on Cognitive Effort: Implications for Cognitive Engagement in Older Adulthood," *Psychology and Aging* 28, no. 2 (2013): 495–504, https://doi.org/10.1037/a0031255.

26. D. M. Yee, S. Adams, A. Beck, and T. S. Braver, "Age-Related Differences in Motivational Integration and Cognitive Control," *Cognitive, Affective, & Behavioral Neuroscience* 19, no. 3 (2019): 692–714, https://doi.org/10.3758/s13415-019-00713-3.

27. F. Sun, I. J. Norman, and A. E. While, "Physical Activity in Older People: A Systematic Review," *BMC Public Health* 13, no. 1 (2013): 449, https://doi.org/10.1186/1471-2458-13-449.

28. L. Smith, B. Gardner, A. Fisher, and M. Hamer, "Patterns and Correlates of Physical Activity Behaviour Over 10 Years in Older Adults: Prospective Analyses From the English Longitudinal Study of Ageing," *BMJ Open* 5, no. 4 (2015): e007423, https://doi.org/10.1136/bmjopen-2014-007423.

29. M. Ayabe, T. Yahiro, M. Yoshioka, H. Higuchi, Y. Higaki, and H. Tanaka, "Objectively Measured Age-Related Changes in the Intensity Distribution of Daily Physical Activity in Adults," *Journal of Physical Activity and Health* 6, no. 4 (2009): 419–425, https://doi.org/10.1123/jpah.6.4.419.

30. R. Nusslock, C. B. Young, and K. S. F. Damme, "Elevated Reward-Related Neural Activation as a Unique Biological Marker of Bipolar Disorder: Assessment and Treatment Implications," *Behaviour Research and Therapy* 62, no. 3 (2014): 74–87, https://doi.org/10.1016/j.brat.2014.08.011.

31. R. Nusslock and L. B. Alloy, "Reward Processing and Mood-Related Symptoms: An RDoC and Translational Neuroscience Perspective," *Journal of Affective Disorders* 216, no. 5 (2017): 3–16, https://doi.org/10.1016/j.jad.2017.02.001.

32. A. E. Whitton, M. T. Treadway, and D. A. Pizzagalli, "Reward Processing Dysfunction in Major Depression, Bipolar Disorder and

Schizophrenia," *Current Opinion in Psychiatry* 28, no. 1 (2015): 7–12, https://doi.org/10.1097/YCO.0000000000000122.

33. UK Biobank, "UK Biobank: Protocol for a Large-Scale Prospective Epidemiological Resource." 06. 2007.

34. D. J. Smith, B. I. Nicholl, B. Cullen, et al., "Prevalence and Characteristics of Probable Major Depression and Bipolar Disorder Within UK Biobank: Cross-Sectional Study of 172,751 Participants," *PLoS One* 8, no. 11 (2013): 1–7, https://doi.org/10.1371/journal.pone.0075362.

35. K. A. S. Davis, J. R. I. Coleman, M. Adams, et al., "Mental Health in UK Biobank—Development, Implementation and Results From an Online Questionnaire Completed by 157 366 Participants: A Reanalysis," *BJPsych Open* 6, no. 2 (2020): 18, https://doi.org/10.1192/bjo.2019.100.

36. M. Anatürk, S. Suri, S. M. Smith, K. P. Ebmeier, and C. E. Sexton, "Leisure Activities and Their Relationship With MRI Measures of Brain Structure, Functional Connectivity, and Cognition in the UK Biobank Cohort," *Frontiers in Aging Neuroscience* 13 (2021): 13, https://doi.org/10.3389/fnagi.2021.734866.

37. P. D. Harvey, "Domains of Cognition and Their Assessment," *Dialogues in Clinical Neuroscience* 21, no. 3 (2019): 227–237, https://doi.org/10.31887/DCNS.2019.21.3/pharvey.

38. P. Townsend, P. Phillimore, and A. Beattie, *Health and Deprivation*, 1st ed. (Routledge, 1988), https://doi.org/10.4324/9781003368885.

39. A. Doherty, D. Jackson, N. Hammerla, et al., "Large Scale Population Assessment of Physical Activity Using Wrist Worn Accelerometers: The UK Biobank Study," *PLoS One* 12, no. 2 (2017): e0169649, https://doi.org/10.1371/journal.pone.0169649.

40. R. Walmsley, S. Chan, K. Smith-Byrne, et al., "Reallocation of Time Between Device-Measured Movement Behaviours and Risk of Incident Cardiovascular Disease," *British Journal of Sports Medicine* 56, no. 18 (2022): 1008–1017, https://doi.org/10.1136/bjsports-2021-104050.

41. B. R. MacIntosh, J. M. Murias, D. A. Keir, and J. M. Weir, "What Is Moderate to Vigorous Exercise Intensity?," *Frontiers in Physiology* 12 (2021): 682233, https://doi.org/10.3389/fphys.2021.682233.

42. I. J. Deary, S. Strand, P. Smith, and C. Fernandes, "Intelligence and Educational Achievement," *Intelligence* 35, no. 1 (2007): 13–21, https://doi.org/10.1016/j.intell.2006.02.001.

43. T. Wolfram, "(Not Just) Intelligence Stratifies the Occupational Hierarchy: Ranking 360 Professions by IQ and Non-Cognitive Traits," *Intelligence* 98 (2023): 101755, https://doi.org/10.1016/j.intell.2023.101755.

44. K. Fujishiro, J. Xu, and F. Gong, "What Does "Occupation" Represent as an Indicator of Socioeconomic Status?: Exploring Occupational Prestige and Health," *Social Science & Medicine* 71, no. 12 (2010): 2100–2107, https://doi.org/10.1016/j.socscimed.2010.09.026.

45. A. E. Bauman, J. F. Sallis, D. A. Dzewaltowski, and N. Owen, "Toward a Better Understanding of the Influences on Physical Activity: The Role of Determinants, Correlates, Causal Variables, Mediators, Moderators, and Confounders," *American Journal of Preventive Medicine* 23, no. 2 (2002): 5–14, https://doi.org/10.1016/S0749-3797(02)00469-5.

46. J. Choi, M. Lee, J. Lee, D. Kang, and J.-Y. Choi, "Correlates Associated With Participation in Physical Activity Among Adults: A Systematic Review of Reviews and Update," *BMC Public Health* 17, no. 1 (2017): 356, https://doi.org/10.1186/s12889-017-4255-2.

47. S. Hélie, F. Shamloo, K. Novak, and D. Foti, "The Roles of Valuation and Reward Processing in Cognitive Function and Psychiatric Disorders," *Annals of the New York Academy of Sciences* 1395, no. 1 (2017): 33–48, https://doi.org/10.1111/nyas.13327.

Supporting Information

Additional supporting information can be found online in the Supporting Information section.