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Exploring the associations of daily movement behaviours and mid-life cognition: a compositional analysis of the 1970 British Cohort Study

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ABSTRACT

Background Movement behaviours (eg, sedentary behaviour (SB), moderate and vigorous physical activity (MVPA), light intensity physical activity (LIPA) and sleep) are linked to cognition, yet the relative importance of each component is unclear, and not yet explored with compositional methodologies.

Objective To (i) assess the associations of different components of daily movement and participant's overall cognition, memory and executive function, and (ii) understand the relative importance of each individual component for cognition.

Methods The 1970 British Cohort Study (BCS70) is a prospective birth cohort study of UK-born adults. At age 46, participants consented to wear an accelerometer device and complete tests of verbal memory and executive function. Compositional linear regression was used to examine cross-sectional associations between 24-hour movement behaviours and standardised cognition scores. Isotemporal substitution was performed to model the effect of reallocating time between components of daily movement on cognition.

Results The sample comprised 4481 participants (52% female). Time in MVPA relative to SB, LIPA and sleep was positively associated with cognition after adjustments for education and occupational physical activity, but additional adjustment for health status attenuated associations. SB relative to all other movements was robustly positively associated with cognition. Modelling time reallocation between components revealed an increase in cognition centile after MVPA theoretically replaced 9 min of SB (OR=1.31; 95% CI 0.09 to 2.50), 7 min of LIPA (1.27; 0.07 to 2.46) or 7 min of sleep (1.20; 0.01 to 2.39).

Conclusions Relative to time spent in other behaviours, greater MVPA and SB was associated with higher cognitive scores. Loss of MVPA time, given its smaller relative amount, appears most deleterious. Efforts should be made to preserve MVPA time, or reinforce it in place of other behaviours.

WHAT IS ALREADY KNOWN ON THIS TOPIC

⇒ Daily movement behaviours are intrinsically co-dependent, yet differentially related to cognition. Sedentary behaviour appears broadly unfavourable, while vigorous physical activities appear favourable.

WHAT THIS STUDY ADDS

⇒ Adopting a novel, compositional approach, moderate and vigorous physical activity (MVPA) relative to all other daily movement behaviours proved most favourable for mid-life cognition.

HOW THIS STUDY MIGHT AFFECT RESEARCH, PRACTICE OR POLICY

⇒ This robust method corroborates a critical role for MVPA in supporting cognition, and efforts should be made to bolster this component of daily movement.

INTRODUCTION

Despite the known health effects of physical activity (PA), only recently have studies explored the positive impacts of PA on cognition.[1 2] Engagement in PA has been linked to the building of cognitive reserve, which delays the onset of cognitive decline in later life.[2 3] However, all aspects of PA, including intensity and volume, decrease throughout the life course, which might have consequences for cognition later in life.[4] Disentangling the most important components of PA for cognition remains a pressing matter, especially in the years preceding the prodromic phase of cognitive decline.[5 6]

Evidence in mid-life is scarce. The few studies using objective measures typically examine one movement intensity while adjusting for one '*opposing*' intensity.[2 7] A recent systematic review reported greater total PA and moderate and vigorous PA (MVPA) as being most beneficial for cognition.[7] Two studies have explored the associations of movement behaviours and cognition using more robust, time-exchange methodologies: one in older adults[8] and one in mid-life.[9] Both cite MVPA as appearing most favourable for global cognition. Neither study, however, captures sleep time, which is typically the largest component of the day. Modelling the contribution of sleep is acutely relevant when examining cognition, as it is a major confounder of test performance.[10]

Approaches to compositional data analysis are established statistical methods for examining multivariate, finite quantities.[11 12] They properly examine the co-dependency of each component of 24-hour movement and can address a gap in current literature by examining the associations of cognition and PA in the context of *all* components of the day.

To deal with the scarcity of previous evidence in mid-life, this study aimed to (i) assess the associations of different components of daily movement

and participant's overall cognition, memory and executive function, and (ii) understand the relative importance of each individual component for cognition.

METHODS

Participants

The 1970 British Cohort Study (BCS70) consists of individuals born across England, Scotland and Wales in 1970 and followed-up throughout childhood and adulthood.[13] Data are available from the UK data service.[14] The follow-up at age 46 was collected in 2016–2018 (n=8581) and involved biometric measurements, completion of health, demographic and lifestyle questionnaires, and the wearing of a thigh-mounted accelerometer device. Participants provided informed consent before participation and ethical approval was obtained from the National Research Ethics Service Committee South East Coast - Brighton and Sussex (ref 15/LO/1446). Inclusion criteria were restricted to participants who consented to wear an accelerometer, returned the device with sufficient wear time (minimum of 1 day with 10 uninterrupted hours), and provided data on all outcomes and covariates (online supplemental eFigure 1).[15]

Measures

Movement behaviours

PA, sedentary behaviour (SB) and sleep time were measured using a thigh-mounted accelerometer device worn continuously for up to 7 days, including for sleeping and bathing, in line with the validated wear protocol[16 17] (activPAL3 micro; PAL Technologies Ltd, Glasgow, UK). The accelerometer device uses a thigh inclination technique considered more sensitive to SB than wrist and hip-worn devices.[17] MVPA time was derived using a step cadence of ≥100.[18] Light intensity PA (LIPA) was derived as the residual from total movement activity. SB was defined as non-sleep time spent sitting or lying. Sleep time was the longest reclining bout between noon and noon each day (minimum ≥2 hours) or any bouts lasting ≥5 hours.[19]

Primary outcome

Participants undertook a computer-administered subset of cognitive tests of verbal memory (immediate and delayed word recall tasks) and executive function (verbal fluency and two-letter cancellation tasks). These measures of cognition have been routinely used in large-scale epidemiological studies.[6 20–24] Immediate and delayed memory tasks involved retrieval of a 10-word list over 2 min and again after a delay. Tests of executive function included a verbal fluency (animal naming) task which scores the number of animals that participants named in 1 min. Processing speed and accuracy was tested using a letter-cancellation task, whereby participants cross out the letters 'P' and 'W' from a grid of letters. Processing speed is the total number of letters screened in the 1 min interval. Processing accuracy is the number of times that 'P' and 'W' is missed. Z-scores were derived for each test and summed to produce an overall composite score as well as a memory and executive function domain score.[20 25]

Covariates

Covariates were selected based on previous literature and encompassed sociodemographic, health and lifestyle factors.[5 7]

Sociodemographic covariates

Sex was coded as female versus male. Lastly, marital status was categorised as '*unmarried*', '*separated, divorced* or *widowed*' and '*married/civil partnership*'.

Age was included as the difference between survey completion and participant birth date.

Highest educational attainment

Education was categorised by highest academic attainment. Answers were categorised as none: *no formal academic qualifications*, lower: *up to age 16*, middle: *up to age 18*, upper: *diploma or degree level* and highest: *higher degree*.

Occupational physical activity

Occupational PA was derived from the EPIC-Norfolk PA questionnaire[26] and operationalised as '*sitting*', '*standing*', '*physical*' or '*heavy manual*' occupations and '*not working*'.

Disability

Disability was measured using the EU Statistics on Income and Living Conditions abbreviated measure of disability[27] and categorised as '*no longstanding health condition*', '*to some extent*' or '*severely hampered*'.

Body mass index (BMI)

Body weight was measured using the Tanita electronic scale, and height was measured using standard protocols. BMI (body mass (kg)/height (m^2) was included as a continuous variable. Where nurse-measured BMI was missing (n=66) this was imputed based on self-reported measurements.

Psychological distress

Psychological distress was binary, measured using the Malaise Inventory, a nine-question scale, with a defined cut-off point of 4 indicating psychological distress.[28]

Health behaviours

Alcohol consumption was categorised as '*abstinent*', '*irregular or regular non-risky*' and '*risky (≥14 weekly units)*' according to the Alcohol Use Disorders Identification Test scale.[29] Smoking status was categorised as '*never*', '*ex-smoker*', '*less than daily*' and '*daily*'.

Statistical analysis

Initial analyses explore the differences of participant's four-part compositions (proportions of the day spent in MVPA, LIPA, SB and sleep) by quartile, using multivariate analysis of variance Pillai's trace test. An isometric log-ratio (ILR) transformation approach was then used to model the association of cognition and daily movement compositions.[12 30] The ILR transformation for compositions of n components produce n-1 ILR coordinates which, together, account for all daily movement behaviour, and can be modelled together without issues of multicollinearity (online supplemental eTable 1).[31] Unadjusted linear regression models estimated the associations between ILR coordinates and composite cognition z-scores. Adjustments for potential confounders and mediators were made in two steps: (i) sociodemographic factors (age, sex, education and occupational PA, marital status); (ii) health and lifestyle factors (BMI, disability, psychological distress and risky health behaviours). Next, using the unadjusted model, minute-by-minute isotemporal substitutions modelled the change in cognition z-score when time was reallocated from one component of movement into another around the sample mean, while holding the others constant. The point at which z-scores showed substantial positive or negative change was defined as the point at which the modelled z-score's 95% CI no longer overlapped with the mean. This change was

converted into the corresponding change in centile. All analyses were conducted using R studio (RStudio team, Boston, Massachusetts, USA, 2020).

Sensitivity analysis

All analyses were repeated with memory and executive function separately. Lastly, we tested a priori hypotheses that the relationship between PA and cognition might differ depending on educational attainment, sex and occupational PA by testing for interaction effects in the unadjusted model. Stratified analyses were conducted in the case of significance. Lastly, the unadjusted model was repeated with all individuals who provided both movement and cognition measures to explore any potential sampling bias.

RESULTS

Participant characteristics

The analytic sample comprised 4481 participants (details of excluded participants are available in online supplemental eFigure 1). Participants were median age 47 years, predominantly white, female (52% female, n=2347), married (66%, n=2954) and had high educational attainment (43% attained 18 years or older), n=1919; table 1). Most participants' alcohol consumption was occasional or non-risky (68%, n=3033) and half had never smoked (50%, n=2260). Those 2959 participants who did consent to accelerometer-wear but were excluded due to device error, insufficient wear time or failing to provide relevant covariates were proportionally more male (p<0.001) and had higher BMI (p<0.001). Participants spent an average of 51 min in MVPA, 5 hours 42 m LIPA, 9 hour 16 m of SB and 8 hour 11 m sleeping (online supplemental eFigure 2). Excluded participants spent significantly longer in LIPA, but other movement behaviour was not otherwise different (online supplemental eFigure 2). Those raw cognitive tests were normally distributed and showed no evidence of floor or ceiling effects, except processing accuracy, in which participants routinely missed no letters (online supplemental eFigure 3,4). Median processing speed was 335(IQR: 117) letters processed and three missed (Q1,Q3: 1,6; table 2). Mean verbal fluency was 24.0 animals named (SD=6.1). Mean immediate recall was 6.7 words (SD=1.4) and delayed recall was 5.6 words (SD=1.8).

Participant time in each movement intensity differed significantly between quartiles of composite cognition z-scores (p<0.001; figure 1). Compared with the sample mean, participants in the upper two quartiles of cognition attained greater proportions of MVPA and SB and less sleep, while the lowest cognition quartile had the highest proportion of LIPA.

Associations of daily compositions and cognition

Linear regressions revealed a positive association between MVPA relative to all other behaviours, and cognition z-scores (online supplemental eTable 2). SB, relative to all other behaviours was also positively associated with cognition. These associations persisted with adjustment for sociodemographic factors. The relationship between cognition and MVPA relative to other behaviours was fully attenuated after further adjustment for health and lifestyle factors. However, SB relative to all other movement remained positively associated with cognition after full adjustment. Conversely, more time spent in LIPA or sleep relative to all behaviours was inversely associated with cognition. However, only more sleep relative to other behaviours remained significantly, inversely associated with cognition with full adjustment.

Table 1 Sample demographics and bias analysis.

Sociodemographic characteristics		Included sample (n=4481)	Excluded sample (n=2959)	Comparison P value
Age at survey	Mean, SD	47 (0.6)	47 (0.7)	0.072
Sex (female)	% (N)	52% (2347)	50% (1483)	0.060
Married	% (N)			
Unmarried		19% (836)	20% (553)	<0.001*
Divorced, separated or widowed		15% (691)	18% (520)	
Married or in civil partnership		66% (2954)	62% (1747)	
Highest educational attainment	% (N)			<0.001*
No formal qualifications		25% (1132)	32% (917)	
GCSE or equivalent		32% (1430)	30% (869)	
A level or equivalent		6% (253)	6% (164)	
Undergraduate degree or equivalent		31% (1407)	27% (765)	
Higher degree		6% (259)	5% (143)	
Occupation type	% (N)			<0.001*
No occupation		8% (377)	12% (291)	
Sitting		51% (2274)	47% (1108)	
Standing		14% (629)	14% (324)	
Physical work		22% (1001)	23% (547)	
Heavy manual work		5% (200)	4% (94)	
Health status and behaviours				
Disability status (EU-SILC)	% (N)			<0.001*
No EU-SILC longstanding health condition		85% (3811)	80% (2379)	
EU-SILC classification, disability to some extent		10% (456)	12% (342)	
EU-SILC classification, severely hampered		5% (214)	8% (236)	
Psychological distress (abbreviated Malaise Scale)	% (N)			<0.001*
High malaise (4+)		17% (768)	21% (520)	
Alcohol consumption (weekly units)	% (N)			<0.001*
None		10% (438)	12% (360)	
Occasional (<14)		68% (3033)	63% (1827)	
Regular, risky (>14)		23% (1010)	25% (726)	
Smoker status	% (N)			<0.001*
Never		50% (2260)	44% (1310)	
Ex-smoker		32% (1446)	32% (933)	
Less than daily		5% (215)	6% (175)	
Daily		12% (560)	18% (541)	
BMI	Mean, SD	28.4 (5.6)	29.0 (6.2)	<0.001*

In the Excluded sample group, results were not available for all. The percentages in this column are based on varying total numbers.
*Significant differences between included and excluded sample characteristics presented at the level $\alpha \leq 0.05$ as indicated by t tests and Pearson's $\chi 2$ test.
BMI, body mass index; EU-SILC, EU-Statistics on Income and Living Conditions.

Isotemporal substitutions

To better understand the joint associations of these behaviours with cognition we modelled the change in cognition z-scores (converted to change in centile) associated with different compositions of the day relative to the sample's mean composition (51 min MVPA, 5 hour 42 min LIPA, 9 hour 16 min SB and 8 hour 11 min sleeping). Using the unadjusted model, we reallocated time from one component into another minute-by-minute while holding the others constant around the mean, to identify the minimum change before z-scores no longer overlapped with the mean. Increased cognition centile was seen after 9 min of SB was replaced with (9 min) MVPA (1.31; 95% CI 0.09 to

Table 2 Raw participant cognitive test scores and comparison with excluded sample.

	Analytic sample (n=4481), median (IQR)	Excluded sample (n=2959), median (IQR)	P value
Processing speed	335 (117)	331 (119)	0.550
Processing accuracy	3 (5)	3 (4)	<0.001*
Verbal fluency	24 (8)	23 (8)	<0.001*
Recall (immediate)	7 (2)	7 (1)	<0.001*
Recall (delayed)	6 (3)	5 (3)	<0.001*

*Significant differences between included and excluded sample characteristics presented at the level $\alpha \leq 0.05$ as indicated by t tests and Pearson's $\chi 2$ test. Processing accuracy is the count of errors (missed letters) on two-letter cancellation task and is inversely scored.

2.50; figure 2), 7 min of LIPA was replaced with MVPA (1.27; 0.07 to 2.46) or 7 min of sleep was replaced with MVPA (1.20; 0.01,2.39).

Replacing LIPA or sleep with SB was also estimated to be favourable for cognition centile, but only after 37 min of LIPA was replaced by SB (1.25; 95% CI 0.03 to 2.48; figure 2) or 56 min of sleep was replaced by SB (1.41; 0.01 to 2.80).

Most adverse for cognition score, however, was the reallocation of time away from MVPA. Reductions in cognition centile were estimated after 8 min of MVPA was replaced by SB (−1.38; −0.16 to –2.59; figure 2), 6 min of MVPA was replaced by LIPA (−1.19; −0.01 to –2.38) or 7 min of MVPA was replaced by sleep (−1.35; −0.15 to –2.55).

Sensitivity analysis

The same relationships were observed when repeating analyses with individual memory and executive function domain z-scores, but proved stronger for memory and weaker for executive function (online supplemental etables 3,4; eFigure 5,6).

There were significant interactions between education and daily movement ($p<0.05$; online supplemental eTable 5) and occupational PA and daily movement ($p<0.10$; online supplemental eTable 6). Time reallocation was then repeated in stratified analysis. Participants with the highest educational attainment or no formal qualifications showed more acute improvement in cognition centile from reallocating time into MVPA, compared with those in formal education up to age 16 (online supplemental eFigure 7). Similar trends were seen for those participants in sitting occupations, compared with those with heavy manual jobs (online supplemental eFigure 8).

Rerunning the unadjusted model including those participants who did provide measures of both the exposure and cognitive outcome, but were excluded because other variables were missing, revealed no substantive differences in the findings (online supplemental eTable 7).

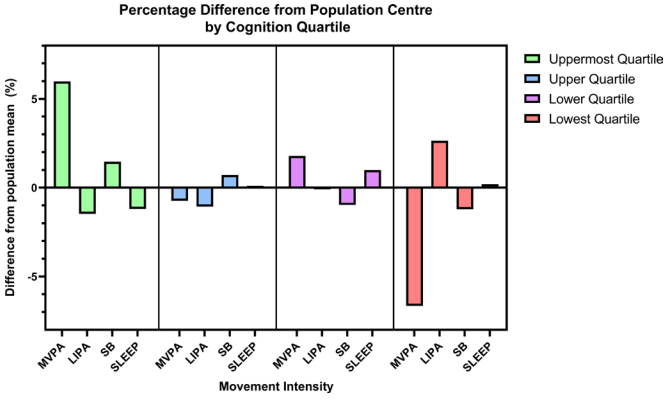

Figure 1 Percentage difference of compositions of daily movement from the sample compositional mean, stratified by composite cognition quartile (quartile 1; highest cognition–quartile 4; lowest cognition). Significant differences in quartile movement compositions were identified (multivariate analysis of variance Pillai's trace test, $p< 0.001$). LIPA, light intensity physical activity; MVPA, moderate and vigorous physical activity; SB, sedentary behaviour.

DISCUSSION

Our aim was to examine associations of different components of daily movement behaviour with mid-life cognition while addressing their co-dependence. Movement profiles of participants were associated with their overall cognition scores. Most notably, MVPA relative to other movement, and SB relative to other behaviours showed positive associations with cognition, with the latter more robust to fuller adjustments. These associations proved stronger for executive function than memory. Our second aim was to explore the relative importance of these associations by modelling time displacements. Permutations of time displacement not involving MVPA (eg, replacing LIPA with SB) proved favourable only after an unrealistic time reallocation. We observed estimated increases in cognition centile after 9 min of MVPA (above the mean) replaced SB, 7 min more MVPA in place of LIPA, or 7 min more MVPA in place of sleep. Displacement of time away from MVPA quickly became adverse for cognition centile. Reallocating 8, 6 and 7 min from the mean of MVPA into SB, LIPA or sleep respectively proved sufficient for decreases in cognition centile. Lastly, stratifying by occupation type revealed that participants with more sedentary jobs might have greater benefit from time being reallocated to MVPA than those participants with manual roles.

The evidence presented here aligns with previous studies, which implicate MVPA as a critical component of daily movement for cognition.[7–9] In high-income countries, greater participation in MVPA is typically reported in higher socioeconomic stratas,[32] where individuals are also more likely to have a sedentary job.[33] However, our models proved robust with adjustments for occupational PA, and may instead suggest a more direct role for MVPA. MVPA is typically the smallest proportion of the day in real terms, and the most difficult intensity to acquire. Perhaps partly for this reason, loss of any MVPA time whatsoever appeared detrimental, even within this relatively active cohort. There are many physiological explanations which may underlie a direct role for MVPA in supporting cognition, including acute increases in cerebral perfusion,[34 35] growth factor release such as brain-derived neurotrophic factor[1] and even hippocampal neurogenesis.[36] Lastly, MVPA, when attained by structured exercise, involves some degree of self-motivation,[37] planning and social interaction, which are all factors considered to be cognitively stimulating.[20 38 39] MVPA relative to other movement proved more strongly associated with executive function, than memory, however, suggesting differences in the possible pathways linking PA to different facets of cognition. Future studies exploring the role of MVPA on cognition should attempt to harmonise accelerometer use with an accurate differentiation of PA attained from leisure time PA with differing cognitive demands.

Despite time reallocation into SB from MVPA being unfavourable for cognition, reallocating time from LIPA or sleep into SB was favourably associated with cognition, but after an unrealistic period. This is contrary to evidence which cites LIPA as favourable and SB as most detrimental.[7] Importantly, our methodology

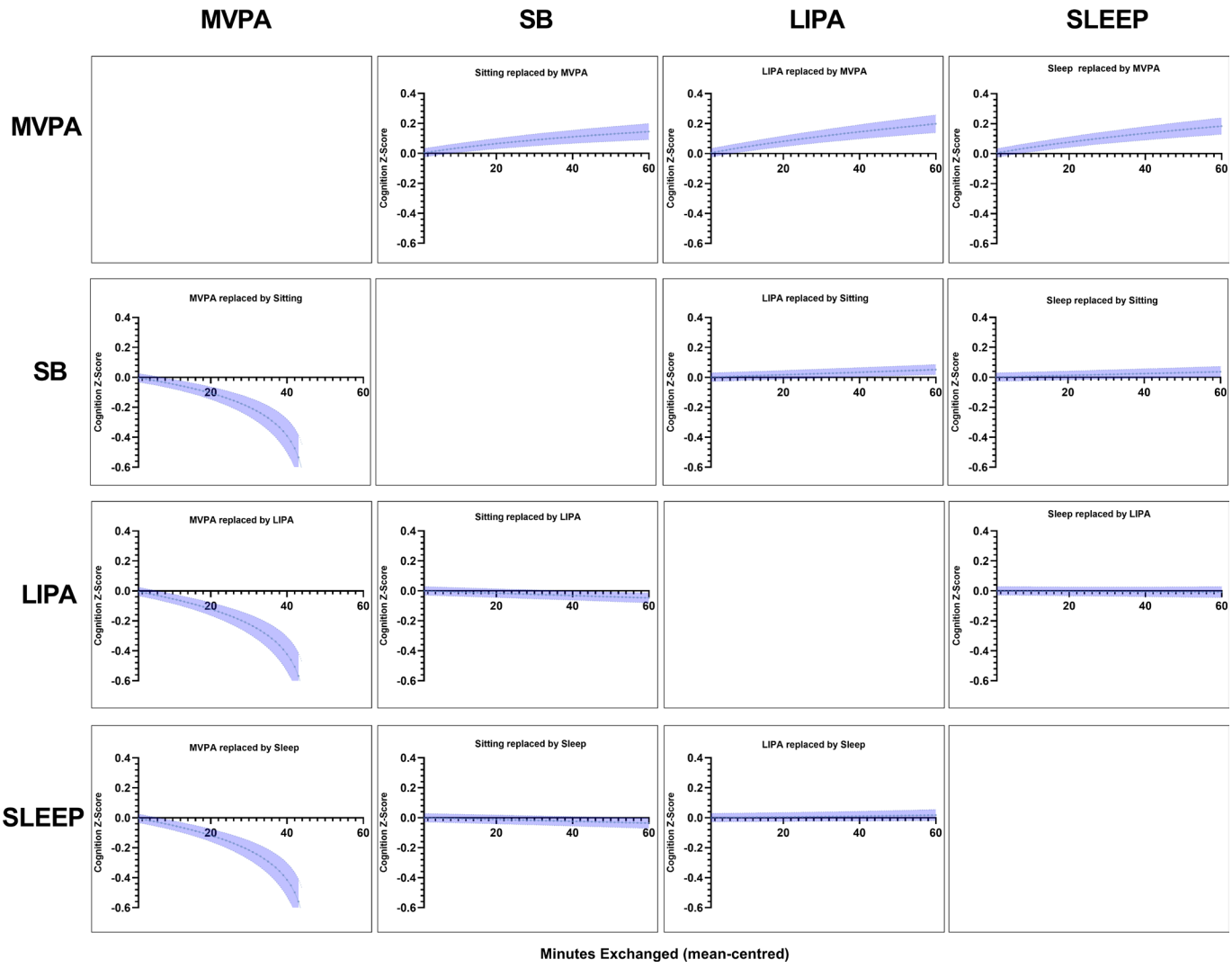

Figure 2 Relative causal effect on composite cognitive z-scores and 95% confidence intervals of isotemporal substitutions between movement components centred at the mean composition, while holding the other two components constant. Substitutions were performed on the first unadjusted isometric log-ratio model presented in online supplemental eTable 2. LIPA, light intensity physical activity; MVPA, moderate and vigorous physical activity; SB, sedentary behaviour.

is distinct from these studies which do not wholly address the co-dependent nature of daily movements. One study however, using a compositional methodology in a mid-life population also observed this apparent benefit of replacing LIPA and sleep time with SB.[2 9] Whitaker *et al*, cite accelerometer inaccuracy specific to waist-mounted devices as accounting for this finding. However, we now corroborate this finding using a thigh-mounted device, less susceptible to misclassification of LIPA as SB.[18]

We hypothesise that these results may reflect the types of activities one may participate in while sedentary rather than there being any '*benefit*' of SB. For instance, participants with more sedentary jobs are likely to have higher educational attainment (a strong predictor of cognition) and perform cognitively stimulating work.[32] Given the cross-sectional nature, it cannot be inferred that change in composition will result in change of cognition, but rather indicates that the most favourable compositions for cognition probably involve only a few minutes greater MVPA. Whereas, we posit that participants with manual jobs may spend less time in SB but longer in LIPA. This is corroborated when stratifying by occupational PA, in which we estimated greater improvement in cognition centile from increasing MVPA in participants in sedentary roles than manual roles. We hypothesise that these findings may be partly explained by distinguishing between SB types (eg, time spent engaging in cognitively stimulating tasks, such as reading or working vs television-viewing).[40] The optimal balance could therefore lie between spending one's SB performing cognitively stimulating tasks, while attaining sufficient MVPA in place of any other behaviour including SB itself, given its relative abundance. Further, these findings, if corroborated by longitudinal analyses, suggest that more-personalised PA guidelines based on key demographic traits are necessary to properly advise individuals on their optimal daily movement behaviours for healthy cognition.

Reallocating time to LIPA was not associated with substantive changes in cognition. LIPA may simply not achieve a threshold intensity to incur any measurable, physiological cognitive benefit, even if providing other cardiometabolic benefits,[2] and may be more critical in older samples. Greater sleep time too was not substantively associated with cognition. Sleep time might have been expected to be positively associated with cognitive performance.[10 22 41] However, accelerometers can only detect

time spent in bed and cannot capture biological sleep. Sleep quality too is arguably more strongly associated with cognitive performance than duration.[10 41] Differentiating between positive and negative SB, and sleep duration and sleep quality are further avenues for exploration.

Strengths and limitations

This study uses both objectively measured PA and a robust compositional analysis approach. The former eliminates the risk of PA recall bias and the latter appropriately examines the co-dependence of each aspect of daily movement. Use of standardised composite cognition scores in this study do not provide the broader detail of global cognition tests, but do allow greater sensitivity than tests which categorise participants based on stringent cut-off points, which might be less relevant to young, healthy adults. This is critical in mid-life where the relationship between each measurable aspect of cognition and our daily movements may be more subtle, and declines in memory and other cognitive abilities through life occur at different rates.[2]

Despite these strengths, accelerometer measures do not provide context for each component of movement. SB can involve activities which have positive or negative associations with cognition.[40]

Despite use of a large sample, the cohort under-represents non-white communities, in which age-related disorders are known to differ in prevalence,[42] limiting the generalisability of these findings to the wider population. Furthermore, participants declining to wear an accelerometer had sociodemographic differences.[18] Individuals excluded because some data were missing also differed from the sample in their degree of LIPA (higher average LIPA), and in some cognitive domains (lower average domain scores) (online supplemental eTables 8 & 9), and we therefore cannot rule out the possible bias this might introduce.

Lastly, to deal with the limitation of this study being cross-sectional, future such studies must now apply a similar analytic approach to longitudinal cognition and 24-hour movement data.

CONCLUSION

The role PA plays in supporting cognition is of increasing interest given the rising prevalence of age-related cognitive decline. This analysis uses a robust compositional approach to implicate MVPA as a critical component of movement for supporting overall cognition, executive function and memory. Redistributing time from MVPA was estimated to be detrimental to all measured facets of cognition after as little as 6 min was replaced by other behaviours. highlighting the importance of bolstering MVPA to support cognition.

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Competing interests None declared.

Patient consent for publication Not applicable.

Ethics approval This study involves human participants and ethical approval was obtained from NRES Committee South East Coast - Brighton and Sussex (Ref 15/LO/1446). Participants gave informed consent to participate in the study before taking part.

Provenance and peer review Not commissioned; externally peer reviewed.

Data availability statement Original study protocol and survey documents can be found online at: https://bcs70.info/ and access to this data is available through the UK data service: UK Data Service ' Series

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