The title

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The authors made the following contributions. First Author: Conceptualization, Writing - Original Draft Preparation, Writing - Review & Editing; Ernst-August Doelle: Writing - Review & Editing, Supervision.

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Abstract

One or two sentences providing a **basic introduction** to the field, comprehensible to a scientist in any discipline.

Keywords: keywords

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Results

The aggregated data-set describes 193,318 observations of daily physical activity and sleep from 24,752 unique participants. Table 1 shows demographic information for all participants. Observations were not uniform across the days of the week $\chi^2_{(6)} = 108.75$, p = $< .001$. There were fewer observations on Monday (z = -8.92) and Sunday (z = -3.54); and more on Wednesday (z = 4.00). A table of study characteristics can be found in supplementary materials.

The effects of physical activity volume on sleep

We estimated the effects of physical activity on sleep (RQ1) using mixed-effects models. We estimated the effect of physical activity volume on sleep by age, and the results are presented in Table 2 and Figure 1 There was no meaningful relationship between physical activity volume and sleep duration. However, we observed a curvilinear relationships between physical activity volume and sleep efficiency, onset, and regularity, all of which interacted with age. Sleep efficiency improved with greater physical activity volume, but improvements tapered off for older individuals. Physical activity volume and sleep onset had a positive association for younger individuals, but a negative association for older individuals, where sleep onset was reduced among those with the highest physical activity. There was a strong positive association between physical activity volume and sleep regularity, which was strongest among older participants. For participants aged 35 years and above, this link weakened among those with a physical activity volume greater than two standard deviations.

The effects of physical activity intensity on sleep

We estimated how physical activity intensity affects sleep across different age groups We present the results controlling for sex, SES, and BMI, in Table 2 and Figure 2. We found

that higher physical activity intensity is directly proportional to longer sleep duration and better sleep efficiency. In the case of older participants, physical activity intensity had a U-shaped relationship with sleep onset, meaning that individuals with very low or very high physical activity intensity had longer sleep onset. We also found a strong link between physical activity intensity and improved sleep regularity, which weakened at higher intensity levels.

The effects of sleep duration on physical activity

We estimated the effect of sleep duration on physical activity by age Results, controlling for sex, SES, and BMI are presented in Table 3 and Figure 3. As age increases, both physical activity volume and intensity decrease. We found a subtle inverted U-shaped relationship between average sleep duration and physical activity volume, where the highest volume of physical activity was linked to average sleep duration.

The effects of sleep efficiency on physical activity

We estimated the effect of sleep efficiency on physical activity by age. Results, controlling for sex, SES, and BMI are presented in Table 3 and Figure 4. We did not find a relationship between physical activity volume and sleep efficiency. However, there was a subtle U-shaped relationship where individuals with above-average sleep efficiency engaged in more intense physical activity.

The effects of sleep onset on physical activity

We estimated the effect of sleep onset on physical activity by age Results, controlling for sex, SES, and BMI are presented in Table 3 and Figure 5. There were strong U-shaped relationships where average sleep onset was linked to the highest levels of physical activity

volume and intensity. The U-shaped relationship between sleep onset and physical activity volume attenuated for older participants.

The effects of sleep regularity on physical activity

We estimated the effect of sleep regularity on physical activity by age. Results, controlling for sex, SES, and BMI are presented in Table 3 and Figure 6. There was a U-shaped relationship between sleep regularity and physical activity volume. Participants with below-average sleep regularity tended to have average physical activity volume. Increases in regularity above the average were linked to greater physical activity volume. There was a strong linear relationship between sleep regularity and physical activity intensity which slightly attenuated with age. Greater sleep regularity was associated with greater physical activity the following day.

Table 1

Participant characteristics

	Age group				
Characteristic	2-11 years	12-18 years	19-35 years	36-65 years	66+ years
Numeric variables					
N	10,065	3,431	373	4,187	6,615
Age	9.58 (1.36)	13.73 (2.40)	22.56 (6.04)	57.77 (6.91)	72.22 (4.74)
BMI	17.98 (3.28)	20.43 (4.01)	24.77 (5.94)	26.99 (4.92)	27.08 (4.41)
Valid weartime hours	21.77 (3.03)	21.20 (3.97)	21.06 (3.46)	22.57 (2.49)	23.78 (1.03)
PA intensity	-2.11 (0.19)	-2.20 (0.19)	-2.35 (0.20)	-2.50 (0.19)	-2.67 (0.22)
PA volume	43.68 (25.56)	42.28 (16.83)	41.37 (11.44)	39.80 (13.35)	31.23 (10.39)
Sleep duration	429.14 (120.91)	374.98 (131.77)	334.95 (108.40)	399.97 (70.13)	397.38 (74.34)
Sleep efficiency	0.78 (0.12)	0.81 (0.15)	0.87 (0.10)	0.87 (0.07)	0.86 (0.06)
Sleep onset	20.89 (1.14)	22.17 (2.03)	24.03 (1.73)	23.66 (1.37)	24.41 (1.32)
Sleep regularity	54.58 (12.72)	54.07 (13.28)	53.13 (13.30)	59.11 (11.76)	54.68 (12.59)
Accelerometer Wear Location					
Hip	7,487 (74.39%)	1,321 (38.50%)	-	-	-
Wrist	2,578 (25.61%)	2,110 (61.50%)	373 (100.00%)	4,187 (100.00%)	6,615 (100.00%)
Ethnicity					
Non-white	1,870 (18.58%)	481 (14.02%)	31 (8.31%)	21 (0.50%)	-
Unclear	4,880 (48.48%)	1,946 (56.72%)	229 (61.39%)	2,361 (56.39%)	5,545 (83.82%)
White	3,315 (32.94%)	1,004 (29.26%)	113 (30.29%)	1,805 (43.11%)	1,070 (16.18%)
Region					
Africa	910 (9.04%)	175 (5.10%)	-	-	-
Asia	635 (6.31%)	95 (2.77%)	-	-	-
Europe	3,002 (29.83%)	1,238 (36.08%)	107 (28.69%)	3,772 (90.09%)	6,612 (99.95%)

Table 1 continued

	Age group				
Characteristic	2-11 years	12-18 years	19-35 years	36-65 years	66+ years
North america	1,342 (13.33%)	85 (2.48%)	-	-	-
Oceania	1,798 (17.86%)	694 (20.23%)	146 (39.14%)	415 (9.91%)	3 (0.05%)
South america	2,378 (23.63%)	1,144 (33.34%)	120 (32.17%)	-	-
Season					
Autumn	3,310 (32.89%)	821 (23.93%)	34 (9.12%)	1,003 (23.96%)	1,412 (21.35%)
Spring	2,320 (23.05%)	1,718 (50.07%)	272 (72.92%)	1,145 (27.35%)	2,149 (32.49%)
Summer	1,260 (12.52%)	372 (10.84%)	30 (8.04%)	956 (22.83%)	1,364 (20.62%)
Winter	3,175 (31.54%)	520 (15.16%)	37 (9.92%)	1,083 (25.87%)	1,690 (25.55%)
Sex					
Female	5,259 (52.25%)	1,757 (51.21%)	232 (62.20%)	2,250 (53.74%)	2,739 (41.41%)
Male	4,806 (47.75%)	1,674 (48.79%)	141 (37.80%)	1,937 (46.26%)	3,876 (58.59%)
Sleep Conditions Reported					
Yes	49 (0.49%)	1 (0.03%)	-	268 (6.40%)	690 (10.43%)
Socioeconomic Status					
Low	3,576 (35.53%)	898 (26.17%)	67 (17.96%)	1,180 (28.18%)	2,505 (37.87%)
Medium	2,798 (27.80%)	1,228 (35.79%)	148 (39.68%)	1,681 (40.15%)	2,589 (39.14%)
High	3,691 (36.67%)	1,305 (38.04%)	158 (42.36%)	1,326 (31.67%)	1,521 (22.99%)

Note. For categorical variables the value is the count, and percentage. For numeric variables the value is the Mean and SD.

N = 24,752

Table 2

Physical activity predicting sleep controlling for SES, sex, and BMI.

Term	β [95% CI]	SE	t	p	β [95% CI]	SE	t	p
(Intercept)	0.19 [-0.58, 0.96]	0.39	0.48	.634	0.20 [-0.03, 0.44]	0.12	1.71	.088
Log pa volume	-0.19 [-0.61, 0.23]	0.21	-0.89	.371	0.08 [0.04, 0.13]	0.02	3.63	< .001
Age	-0.02 [-0.04, 0.00]	0.01	-1.57	.117	0.00 [-0.01, 0.00]	0.00	-0.99	.320
Log pa volume^2	0.05 [-0.01, 0.11]	0.03	1.75	.081	0.01 [-0.01, 0.04]	0.01	1.06	.288
Log pa volume × age	0.01 [0.00, 0.02]	0.01	1.56	.119	0.00 [0.00, 0.00]	0.00	-1.05	.294
Age × log pa volume^2	0.00 [0.00, 0.00]	0.00	-1.66	.096	0.00 [0.00, 0.00]	0.00	-1.06	.289
(Intercept)	-1.80 [-2.59, -1.02]	0.40	-4.51	< .001	0.29 [0.03, 0.54]	0.13	2.21	.028
Log pa volume	1.03 [0.61, 1.46]	0.22	4.77	< .001	0.04 [0.00, 0.09]	0.02	1.75	.080
Age	0.03 [0.01, 0.05]	0.01	2.48	.013	0.00 [0.00, 0.01]	0.00	0.84	.400
Log pa volume^2	-0.13 [-0.19, -0.07]	0.03	-4.08	< .001	-0.02 [-0.05, 0.00]	0.01	-1.75	.080
Log pa volume × age	-0.01 [-0.02, 0.00]	0.01	-1.84	.066	0.00 [0.00, 0.00]	0.00	-1.65	.100
Age × log pa volume^2	0.00 [0.00, 0.00]	0.00	1.37	.170	0.00 [0.00, 0.00]	0.00	1.12	.261
(Intercept)	-0.84 [-1.49, -0.20]	0.33	-2.56	.011	0.05 [-0.28, 0.39]	0.17	0.32	.753
Log pa volume	0.54 [0.23, 0.85]	0.16	3.42	.001	-0.06 [-0.10, -0.03]	0.02	-3.55	< .001
Age	0.02 [0.01, 0.04]	0.01	2.79	.005	0.00 [0.00, 0.00]	0.00	-0.69	.493
Log pa volume^2	-0.08 [-0.12, -0.04]	0.02	-3.56	< .001	-0.02 [-0.04, 0.00]	0.01	-2.16	.031
Log pa volume × age	-0.01 [-0.02, 0.00]	0.00	-2.36	.018	0.00 [0.00, 0.00]	0.00	0.29	.776
Age × log pa volume^2	0.00 [0.00, 0.00]	0.00	1.72	.086	0.00 [0.00, 0.00]	0.00	2.42	.015
(Intercept)	-2.57 [-3.30, -1.84]	0.37	-6.88	< .001	0.57 [0.33, 0.81]	0.12	4.64	< .001
Log pa volume	1.32 [0.92, 1.72]	0.20	6.49	< .001	0.27 [0.23, 0.31]	0.02	12.26	< .001
Age	-0.03 [-0.05, -0.01]	0.01	-2.80	.006	0.00 [-0.01, 0.00]	0.00	-1.45	.147
Log pa volume^2	-0.13 [-0.19, -0.08]	0.03	-4.65	< .001	-0.11 [-0.13, -0.08]	0.01	-8.23	< .001

Table 2 continued

Term	β [95% CI]	SE	t	p	β [95% CI]	SE	t	p
Log pa volume × age	0.02 [0.01, 0.03]	0.01	3.11	.002	0.00 [-0.01, 0.00]	0.00	-9.46	$< .001$
Age × log pa volume^2	0.00 [0.00, 0.00]	0.00	-3.29	.001	0.00 [0.00, 0.00]	0.00	2.98	.003

Note. Adjusted for SES, sex, and BMI. Outcomes variables are listed in the column headers.

Table 3

Sleep predicting physical activity controlling for SES, sex, and BMI

Term	β [95% CI]	SE	t	p	β [95% CI]	SE	t	p
(Intercept)	4.33 [4.15, 4.51]	0.09	47.36	< .001	1.36 [1.12, 1.60]	0.12	11.08	< .001
Sleep duration	0.00 [-0.01, 0.01]	0.01	0.01	.989	-0.01 [-0.03, 0.01]	0.01	-1.06	.291
Age	-0.01 [-0.01, -0.01]	0.00	-11.01	< .001	-0.03 [-0.03, -0.02]	0.00	-15.63	< .001
Sleep duration^2	-0.01 [-0.01, 0.00]	0.00	-3.59	< .001	-0.02 [-0.03, -0.01]	0.00	-3.30	.001
Sleep duration × age	0.00 [0.00, 0.00]	0.00	-1.58	.115	0.00 [0.00, 0.00]	0.00	2.39	.017
Age × Sleep duration^2	0.00 [0.00, 0.00]	0.00	-1.25	.211	0.00 [0.00, 0.00]	0.00	1.30	.193
(Intercept)	4.32 [4.14, 4.49]	0.09	47.46	< .001	1.34 [1.10, 1.58]	0.12	10.94	< .001
Sleep efficiency	0.02 [0.00, 0.03]	0.01	2.57	.013	0.02 [0.00, 0.05]	0.01	1.87	.065
Age	-0.01 [-0.01, -0.01]	0.00	-10.93	< .001	-0.03 [-0.03, -0.02]	0.00	-15.48	< .001
Sleep efficiency^2	0.00 [0.00, 0.00]	0.00	-0.06	.955	0.00 [0.00, 0.01]	0.00	0.83	.409
Sleep efficiency × age	0.00 [0.00, 0.00]	0.00	-1.75	.083	0.00 [0.00, 0.00]	0.00	-1.66	.097
Age × Sleep efficiency^2	0.00 [0.00, 0.00]	0.00	-0.69	.489	0.00 [0.00, 0.00]	0.00	-0.49	.623
(Intercept)	4.32 [4.14, 4.50]	0.09	47.34	< .001	1.35 [1.11, 1.59]	0.12	10.94	< .001
Sleep onset	0.01 [-0.01, 0.02]	0.01	0.97	.330	0.02 [0.00, 0.05]	0.01	2.02	.043
Age	-0.01 [-0.01, -0.01]	0.00	-10.98	< .001	-0.03 [-0.03, -0.02]	0.00	-15.64	< .001
Sleep onset^2	-0.01 [-0.02, 0.00]	0.01	-1.19	.233	-0.01 [-0.03, 0.01]	0.01	-0.62	.532
Sleep onset × age	0.00 [0.00, 0.00]	0.00	-0.04	.968	0.00 [0.00, 0.00]	0.00	-0.91	.361
Age × Sleep onset^2	0.00 [0.00, 0.00]	0.00	-0.50	.614	0.00 [0.00, 0.00]	0.00	1.00	.317
(Intercept)	4.29 [4.11, 4.47]	0.09	47.79	< .001	1.33 [1.10, 1.57]	0.12	11.00	< .001
Sleep regularity	0.08 [0.07, 0.09]	0.01	12.76	< .001	0.09 [0.07, 0.11]	0.01	7.67	< .001
Age	-0.01 [-0.01, -0.01]	0.00	-11.03	< .001	-0.03 [-0.03, -0.02]	0.00	-15.66	< .001
Sleep regularity^2	-0.01 [-0.01, 0.00]	0.00	-2.39	.017	0.00 [-0.02, 0.01]	0.01	-0.64	.522

Table 3 continued

Term	β [95% CI]	SE	t	p	β [95% CI]	SE	t	p
Sleep regularity × age	0.00 [0.00, 0.00]	0.00	-2.97	.003	0.00 [0.00, 0.00]	0.00	-5.10	< .001
Age × Sleep regularity^2	0.00 [0.00, 0.00]	0.00	-0.73	.466	0.00 [0.00, 0.00]	0.00	-1.69	.091

Note. Adjusted for SES, sex, and BMI. Outcomes variables are listed in the row headers.

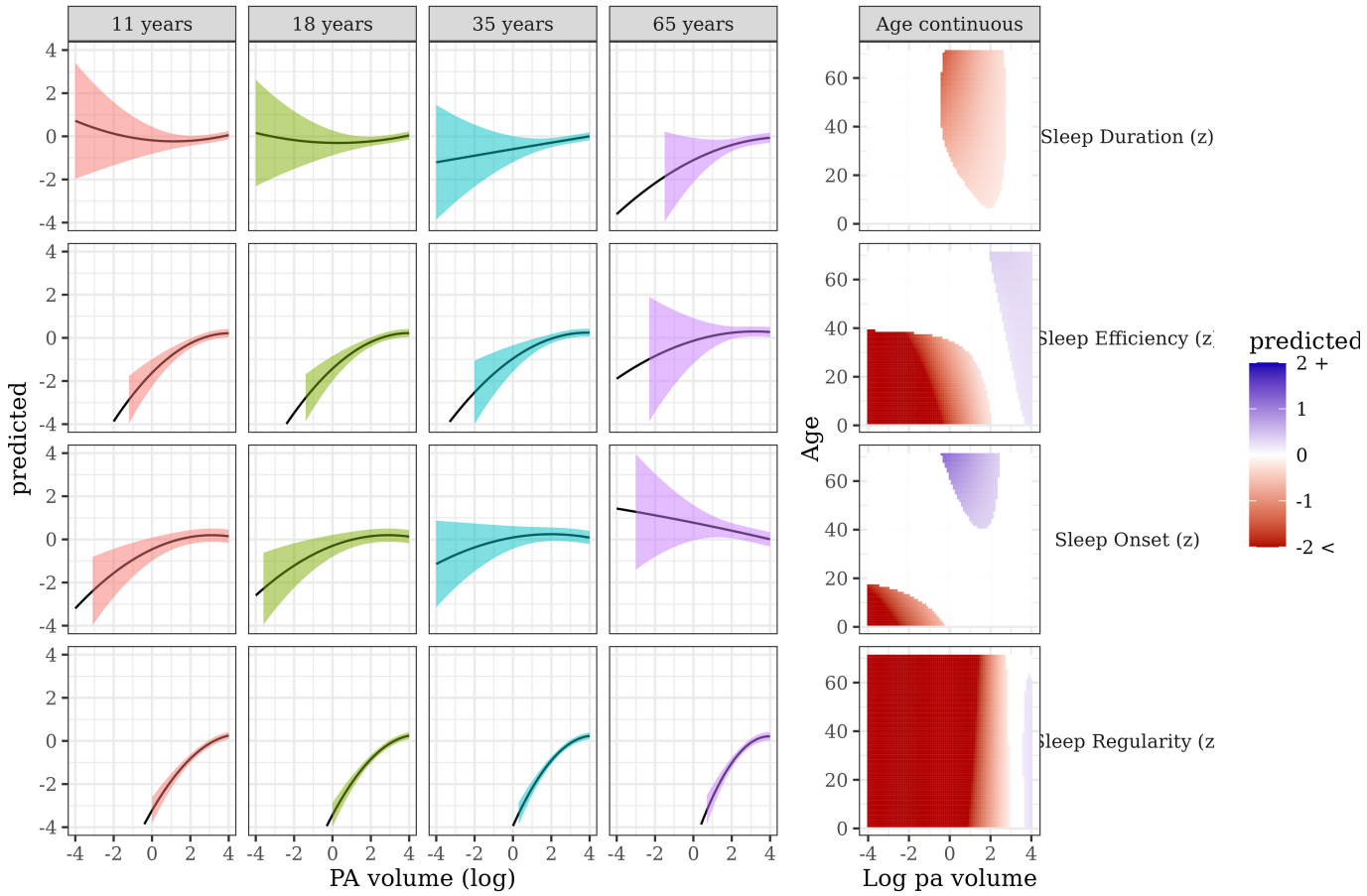

Figure 1. Sleep metrics on physical activity volume. The panels on the left show the curvilinear relationship between PA volume and each of the sleep outcomes at the ages indicated in each column. The panels on the right show the same relationships but by age continuously. The white band indicates predictions which were not significantly different from zero. These plots demonstrate exact turning points where the effects of PA volume change by age.

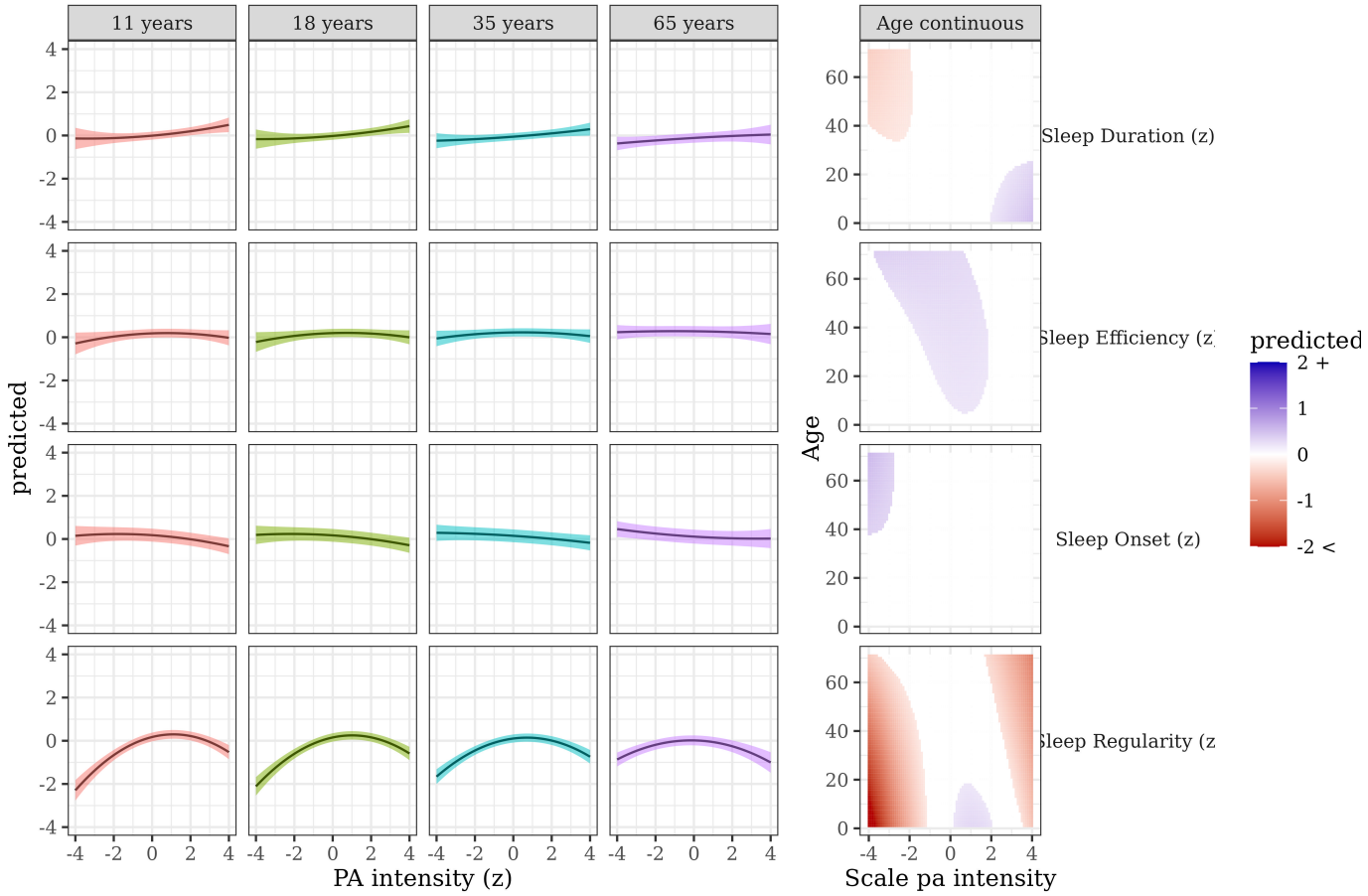

Figure 2. Sleep metrics on physical activity intensity. The panels on the left show the curvilinear relationship between PA intensity and each of the sleep outcomes at the ages indicated in each column. The panels on the right show the same relationships but by age continuously. The white band indicates predictions which were not significantly different from zero.

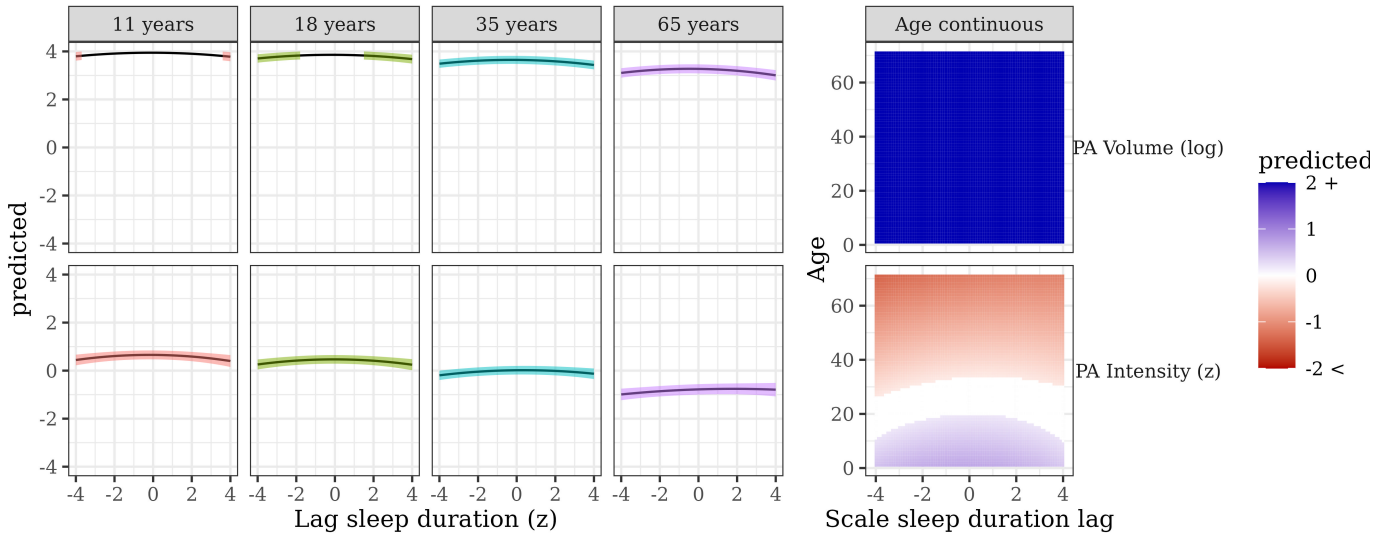

Figure 3. Physical activity by sleep duration. The panels on the left show the curvilinear relationship between sleep duration and each of the physical activity outcomes at the ages indicated in each column. The panels on the right show the same relationships but by age continuously. The white band indicates predictions which were not significantly different from zero.

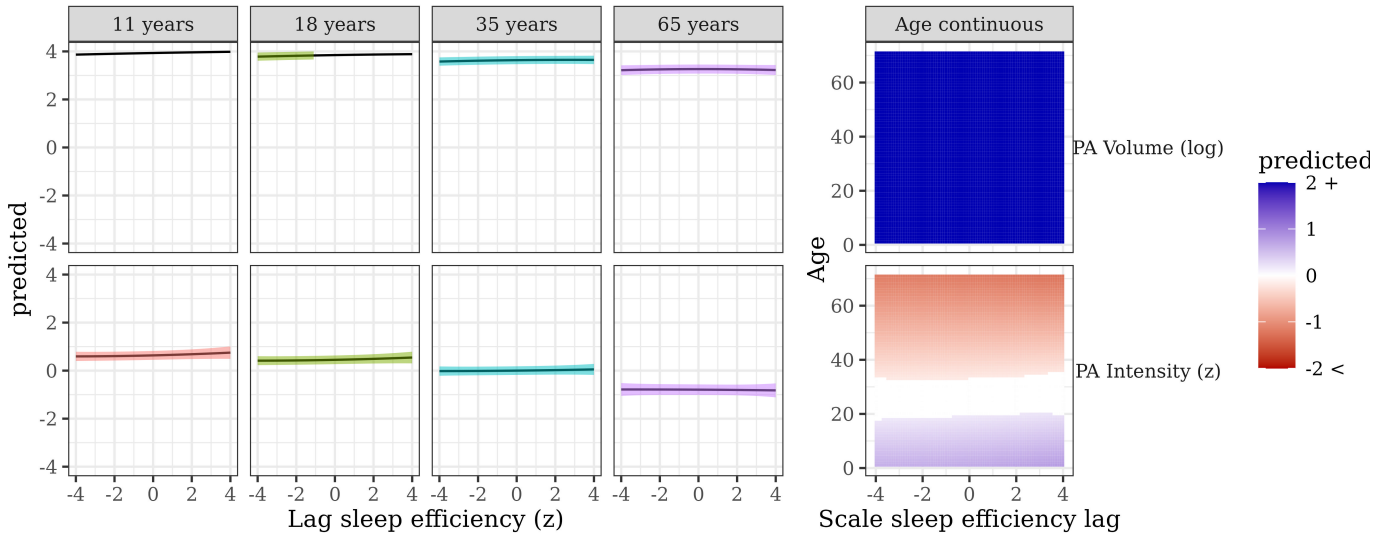

Figure 4. Physical activity by sleep efficiency. The panels on the left show the curvilinear relationship between sleep efficiency and each of the physical activity outcomes at the ages indicated in each column. The panels on the right show the same relationships but by age continuously. The white band indicates predictions which were not significantly different from zero.

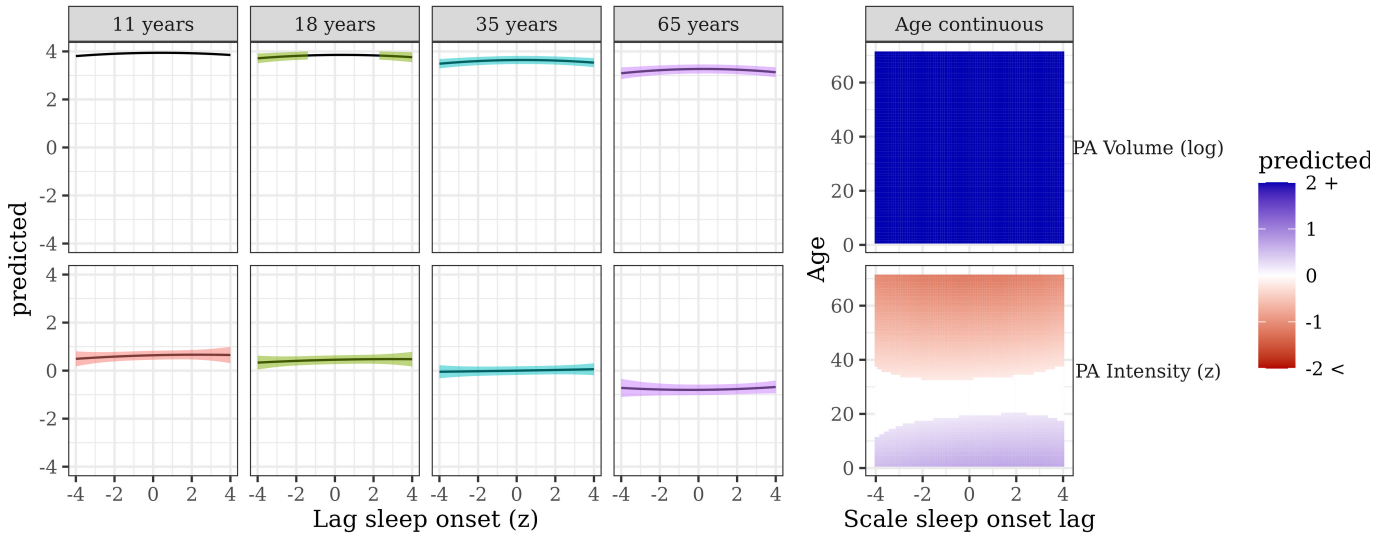

Figure 5. Physical activity by sleep onset. The panels on the left show the curvilinear relationship between sleep onset and each of the physical activity outcomes at the ages indicated in each column. The panels on the right show the same relationships but by age continuously. The white band indicates predictions which were not significantly different from zero.

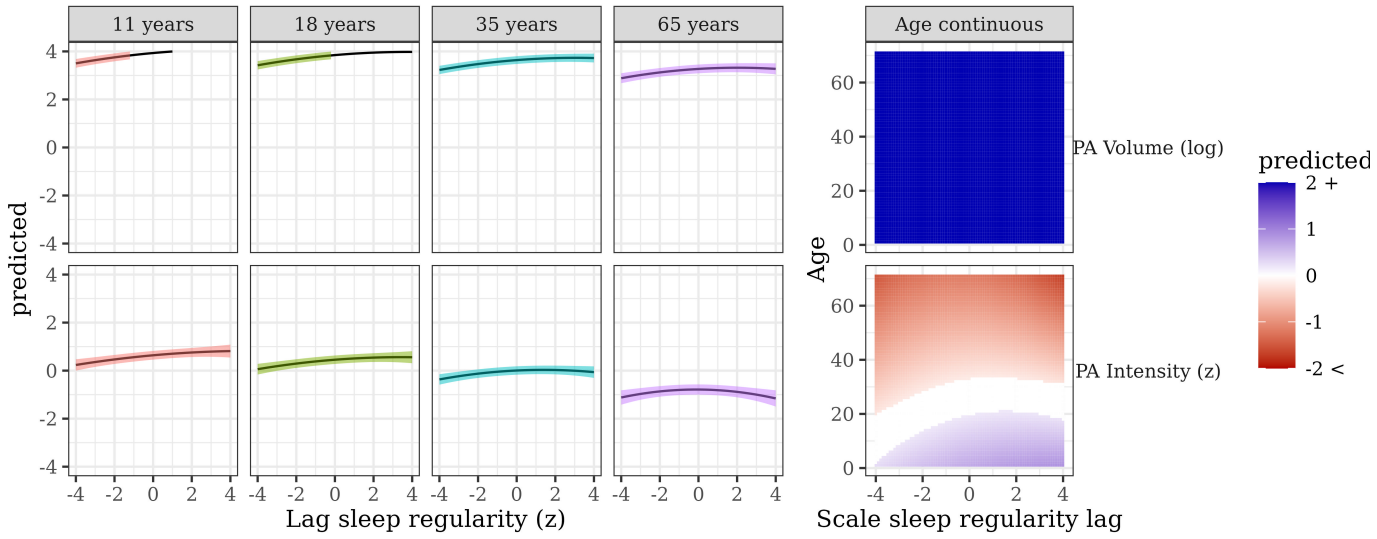

Figure 6. Physical activity by sleep regularity. The panels on the left show the curvilinear relationship between sleep regularity and each of the physical activity outcomes at the ages indicated in each column. The panels on the right show the same relationships but by age continuously. The white band indicates predictions which were not significantly different from zero.