The title

First Author[1] & Ernst-August Doelle[1,2]

[1] Wilhelm-Wundt-University

[2] Konstanz Business School

Author Note

Add complete departmental affiliations for each author here. Each new line herein must be indented, like this line.

Enter author note here.

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

Correspondence concerning this article should be addressed to First Author, Postal address. E-mail: my@email.com

Abstract

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

Keywords: keywords

Word count: X

The title

Results

The aggregated data-set describes 314,925 observations of daily physical activity and sleep from 24,935 unique participants. Table **??** shows demographic information for all participants. 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 3 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 4 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 5 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 6 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 7 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

Variable	Value
Numeric variables	
Valid weartime hours	18.01 (5.41)
PA volume	39.39 (19.84)
PA intensity	-2.34 (0.31)
Sleep duration	387.49 (110.41)
Sleep efficiency	0.77 (0.14)
Sleep onset	22.55 (2.11)
Sleep regularity	55.03 (12.77)
Age	35.28 (28.33)
BMI	21.74 (5.92)
Accelerometer Wear Location	
Hip	8,830 (35.41%)
Wrist	16,105 (64.59%)
Region	
Africa	1,090 (4.37%)
Asia	731 (2.93%)
Europe	14,840 (59.51%)
North america	1,449 (5.81%)
Oceania	3,183 (12.77%)
South america	3,642 (14.61%)
Season	
Autumn	6,644 (26.65%)
Spring	7,874 (31.58%)
Summer	4,137 (16.59%)
Winter	6,280 (25.19%)
Sex	
Female	12,393 (49.70%)
Male	12,542 (50.30%)
Sleep Conditions Reported	
Yes	1,009 (4.05%)
Socioeconomic Status	
Low	8,375 (33.59%)
Medium	8,510 (34.13%)
High	8,050 (32.28%)

Note. For categorical variables the value is the count, and percentage. For numeric variables the value is the Mean and SD. N = 24,935

Table 2

Sleep on physical activity volume controlling for SES, gender and BMI

Term	β [95% CI]	SE	t	p
Sleep duration				
(Intercept)	-0.23 [-0.55, 0.10]	0.17	-1.37	.189
Scale PA volume	0.02 [-0.04, 0.08]	0.03	0.68	.528
Age	0.00 [0.00, 0.00]	0.00	-1.20	.231
Scale PA volume^2	0.00 [-0.01, 0.02]	0.01	0.55	.593
Scale PA volume:age	0.00 [0.00, 0.00]	0.00	1.20	.249
Age:scale PA volume^2	0.00 [0.00, 0.00]	0.00	-0.89	.399
Sleep efficiency				
(Intercept)	-1.03 [-1.51, -0.54]	0.25	-4.15	.005
Scale PA volume	0.20 [0.16, 0.24]	0.02	10.34	$< .001$
Age	0.01 [0.01, 0.01]	0.00	9.72	.003
Scale PA volume^2	-0.02 [-0.03, -0.01]	0.01	-3.04	.005
Scale PA volume:age	0.00 [0.00, 0.00]	0.00	-3.07	.005
Age:scale PA volume^2	0.00 [0.00, 0.00]	0.00	-0.54	.618
Sleep onset				
(Intercept)	-1.01 [-1.15, -0.87]	0.07	-14.16	$< .001$
Scale PA volume	0.13 [0.10, 0.16]	0.02	7.65	$< .001$
Age	0.02 [0.02, 0.02]	0.00	32.14	$< .001$
Scale PA volume^2	-0.02 [-0.03, 0.00]	0.01	-2.78	.048
Scale PA volume:age	0.00 [0.00, 0.00]	0.00	-8.47	$< .001$
Age:scale PA volume^2	0.00 [0.00, 0.00]	0.00	1.61	.179
Sleep regularity				
(Intercept)	-0.05 [-0.29, 0.18]	0.12	-0.43	.697
Scale PA volume	0.33 [0.29, 0.37]	0.02	17.05	$< .001$
Age	0.01 [0.00, 0.01]	0.00	4.53	.032
Scale PA volume^2	-0.03 [-0.04, -0.02]	0.00	-6.18	$< .001$
Scale PA volume:age	0.00 [0.00, 0.00]	0.00	0.71	.486
Age:scale PA volume^2	0.00 [0.00, 0.00]	0.00	-3.87	$< .001$

Note. Adjusted for SES, BMI, and sex.

Table 3

Sleep on physical activity intensity controlling for SES, gender and BMI

Term	β [95% CI]	SE	t	p
Sleep duration				
(Intercept)	-0.26 [-0.60, 0.09]	0.18	-1.46	.171
Scale PA intensity	0.07 [0.03, 0.12]	0.02	3.23	.001
Age	0.00 [0.00, 0.00]	0.00	0.03	.978
Scale PA intensity^2	-0.01 [-0.04, 0.02]	0.02	-0.53	.596
Scale PA intensity:age	0.00 [0.00, 0.00]	0.00	-1.51	.130
Age:scale PA intensity^2	0.00 [0.00, 0.00]	0.00	-0.58	.565
Sleep efficiency				
(Intercept)	-1.09 [-1.61, -0.57]	0.27	-4.11	.007
Scale PA intensity	0.08 [0.02, 0.14]	0.03	2.55	.030
Age	0.01 [0.01, 0.02]	0.00	8.36	.006
Scale PA intensity^2	0.00 [-0.03, 0.04]	0.02	0.17	.863
Scale PA intensity:age	0.00 [0.00, 0.00]	0.00	-1.32	.220
Age:scale PA intensity^2	0.00 [0.00, 0.00]	0.00	-1.00	.325
Sleep onset				
(Intercept)	-0.98 [-1.15, -0.81]	0.09	-11.35	.001
Scale PA intensity	-0.03 [-0.07, 0.01]	0.02	-1.33	.213
Age	0.02 [0.02, 0.02]	0.00	28.96	$< .001$
Scale PA intensity^2	-0.01 [-0.04, 0.01]	0.01	-1.09	.293
Scale PA intensity:age	0.00 [0.00, 0.00]	0.00	-0.49	.627
Age:scale PA intensity^2	0.00 [0.00, 0.00]	0.00	2.45	.032
Sleep regularity				
(Intercept)	-0.15 [-0.31, 0.02]	0.08	-1.75	.126
Scale PA intensity	0.28 [0.22, 0.34]	0.03	9.38	$< .001$
Age	0.01 [0.01, 0.01]	0.00	5.33	.019
Scale PA intensity^2	-0.04 [-0.07, -0.01]	0.01	-2.73	.010
Scale PA intensity:age	0.00 [0.00, 0.00]	0.00	-4.61	.001
Age:scale PA intensity^2	0.00 [0.00, 0.00]	0.00	0.24	.810

Note. Adjusted for SES, BMI, and sex.

Table 4

Physical activity by sleep duration controlling for SES, gender and BMI

Term	β [95% CI]	SE	t	p
PA volume				
(Intercept)	0.44 [0.06, 0.82]	0.20	2.25	.133
Scale sleep duration lag	0.00 [-0.03, 0.03]	0.01	0.00	.997
Age	-0.01 [-0.01, -0.01]	0.00	-6.56	.004
Scale sleep duration lag^2	-0.02 [-0.03, 0.00]	0.01	-2.58	.024
Scale sleep duration lag:age	0.00 [0.00, 0.00]	0.00	-1.21	.251
Age:scale sleep duration lag^2	0.00 [0.00, 0.00]	0.00	0.53	.596
PA intensity				
(Intercept)	0.99 [0.60, 1.37]	0.20	5.01	.032
Scale sleep duration lag	0.02 [-0.01, 0.05]	0.02	1.18	.292
Age	-0.02 [-0.03, -0.02]	0.00	-20.12	.001
Scale sleep duration lag^2	0.00 [-0.01, 0.01]	0.01	-0.64	.526
Scale sleep duration lag:age	0.00 [0.00, 0.00]	0.00	-0.02	.987
Age:scale sleep duration lag^2	0.00 [0.00, 0.00]	0.00	-1.13	.259

Note. Adjusted for SES, BMI, and sex.

Table 5

Physical activity by sleep efficiency controlling for SES, gender and BMI

Term	β [95% CI]	SE	t	p
PA volume				
(Intercept)	0.42 [0.03, 0.81]	0.20	2.11	.151
Scale sleep efficiency lag	0.04 [-0.02, 0.10]	0.03	1.44	.238
Age	-0.01 [-0.01, -0.01]	0.00	-6.63	.004
Scale sleep efficiency lag^2	0.01 [0.00, 0.02]	0.01	1.23	.270
Scale sleep efficiency lag:age	0.00 [0.00, 0.00]	0.00	-0.77	.467
Age:scale sleep efficiency lag^2	0.00 [0.00, 0.00]	0.00	-0.23	.815
PA intensity				
(Intercept)	0.99 [0.60, 1.37]	0.20	5.03	.032
Scale sleep efficiency lag	0.03 [0.00, 0.07]	0.02	2.05	.058
Age	-0.02 [-0.03, -0.02]	0.00	-19.00	.001
Scale sleep efficiency lag^2	0.01 [0.00, 0.02]	0.00	2.39	.019
Scale sleep efficiency lag:age	0.00 [0.00, 0.00]	0.00	-0.62	.544
Age:scale sleep efficiency lag^2	0.00 [0.00, 0.00]	0.00	-0.87	.393

Note. Adjusted for SES, BMI, and sex.

Table 6

Physical activity by sleep onset controlling for SES, gender and BMI

Term	β [95% CI]	SE	t	p
PA volume				
(Intercept)	0.47 [0.08, 0.87]	0.20	2.36	.124
Scale sleep onset lag	0.03 [-0.01, 0.06]	0.02	1.63	.130
Age	-0.01 [-0.01, -0.01]	0.00	-7.41	.002
Scale sleep onset lag^2	-0.05 [-0.07, -0.03]	0.01	-4.52	.001
Scale sleep onset lag:age	0.00 [0.00, 0.00]	0.00	-1.62	.112
Age:scale sleep onset lag^2	0.00 [0.00, 0.00]	0.00	2.64	.017
PA intensity				
(Intercept)	1.04 [0.65, 1.43]	0.20	5.20	.030
Scale sleep onset lag	0.03 [0.00, 0.06]	0.01	2.10	.040
Age	-0.02 [-0.03, -0.02]	0.00	-21.47	$< .001$
Scale sleep onset lag^2	-0.02 [-0.04, -0.01]	0.01	-2.77	.010
Scale sleep onset lag:age	0.00 [0.00, 0.00]	0.00	-0.29	.782
Age:scale sleep onset lag^2	0.00 [0.00, 0.00]	0.00	0.89	.396

Note. Adjusted for SES, BMI, and sex.

Table 7

Physical activity by sleep regularity controlling for SES, gender and BMI

Term	β [95% CI]	SE	t	p
PA volume				
(Intercept)	0.38 [-0.02, 0.79]	0.21	1.84	.191
Scale sleep regularity lag	0.20 [0.17, 0.23]	0.02	12.05	< .001
Age	-0.01 [-0.01, -0.01]	0.00	-6.06	.008
Scale sleep regularity lag^2	0.03 [0.02, 0.04]	0.01	4.32	< .001
Scale sleep regularity lag:age	0.00 [0.00, 0.00]	0.00	-5.07	.001
Age:scale sleep regularity lag^2	0.00 [0.00, 0.00]	0.00	-1.31	.242
PA intensity				
(Intercept)	0.98 [0.59, 1.38]	0.20	4.87	.035
Scale sleep regularity lag	0.11 [0.09, 0.13]	0.01	10.15	< .001
Age	-0.02 [-0.03, -0.02]	0.00	-19.24	.001
Scale sleep regularity lag^2	0.01 [-0.01, 0.02]	0.01	0.85	.421
Scale sleep regularity lag:age	0.00 [0.00, 0.00]	0.00	-4.01	< .001
Age:scale sleep regularity lag^2	0.00 [0.00, 0.00]	0.00	-0.12	.903

Note. Adjusted for SES, BMI, and sex.

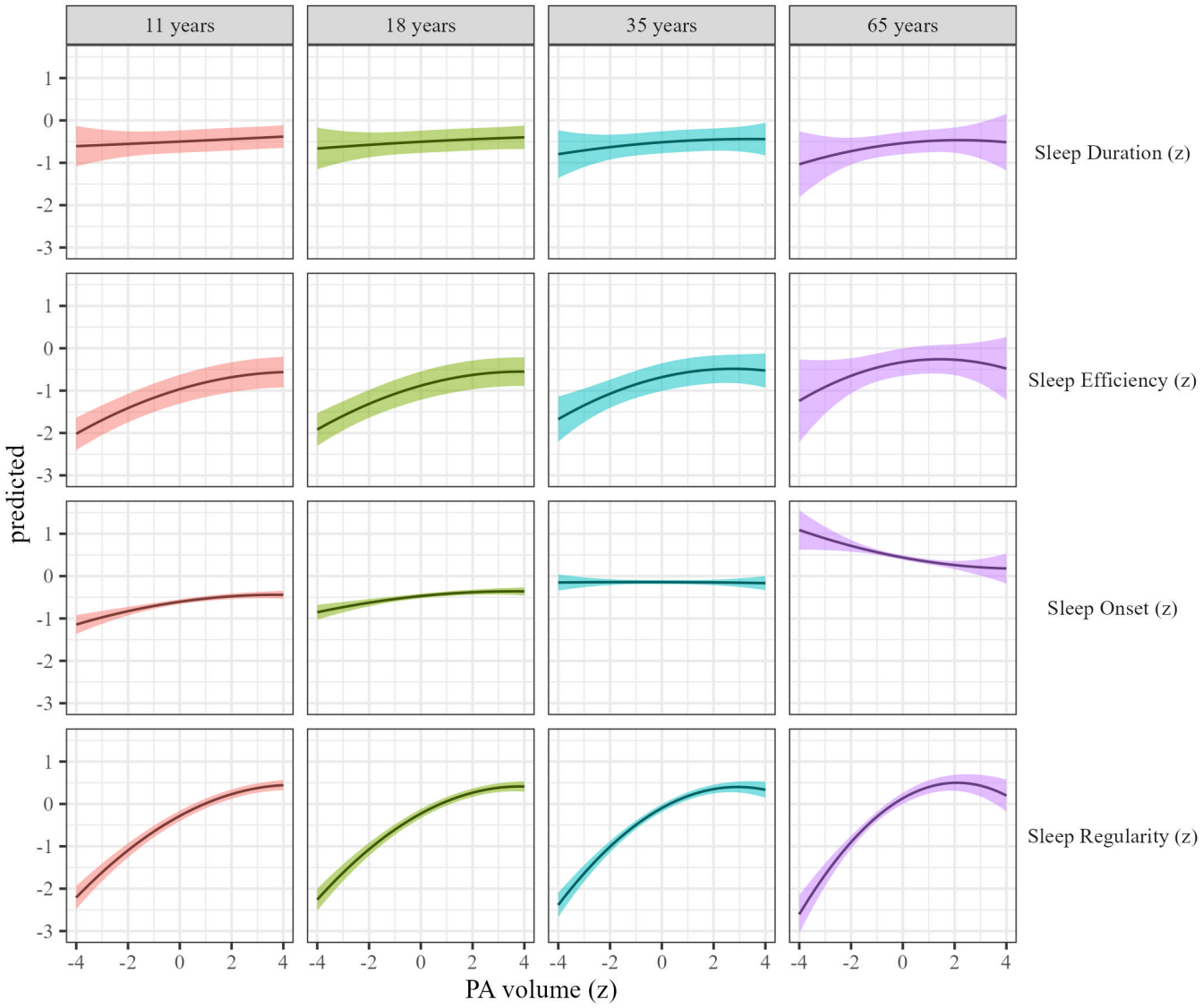

Figure 1. Sleep metrics on Physical activity volume

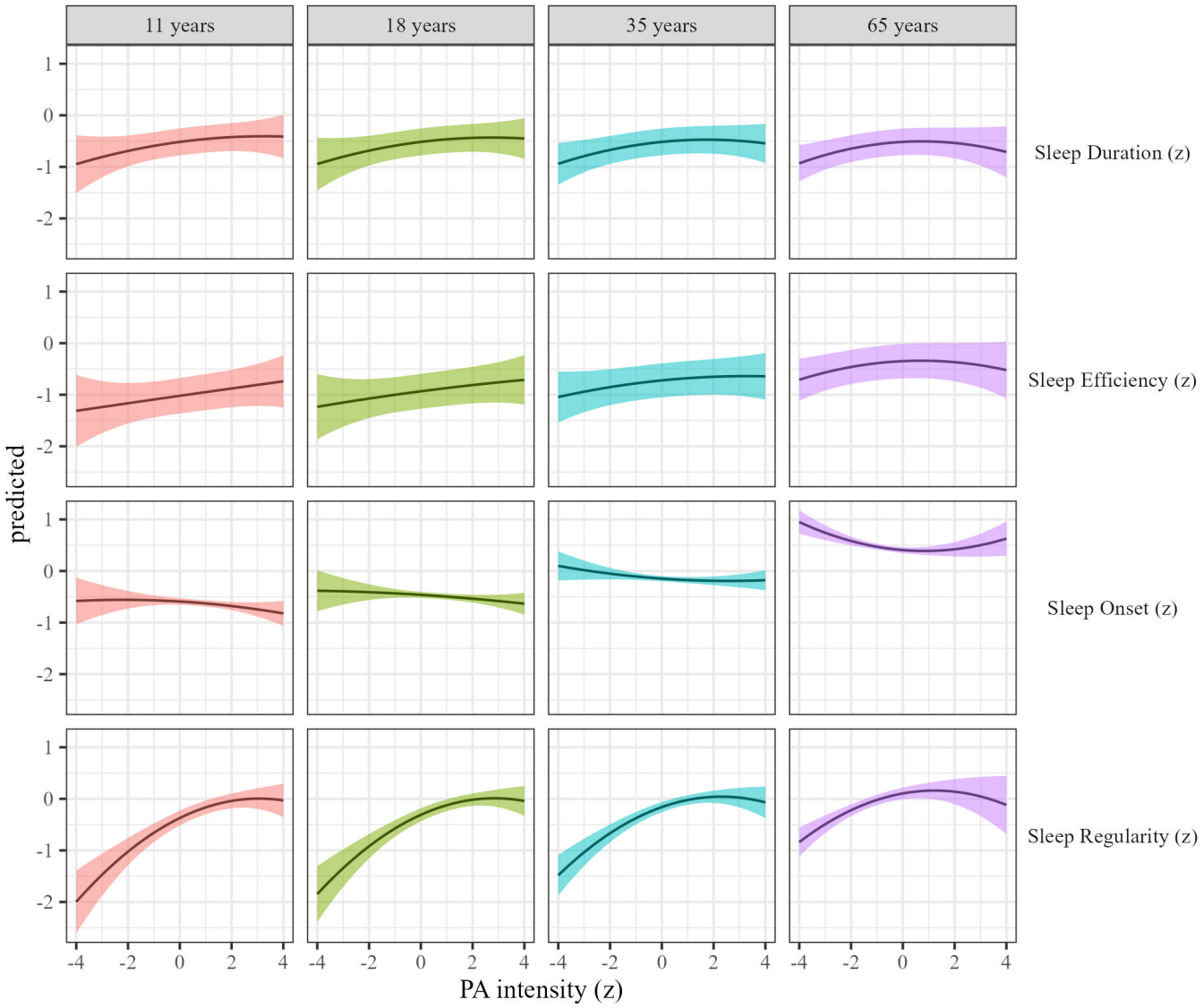

Figure 2. Sleep metrics on Physical activity intensity

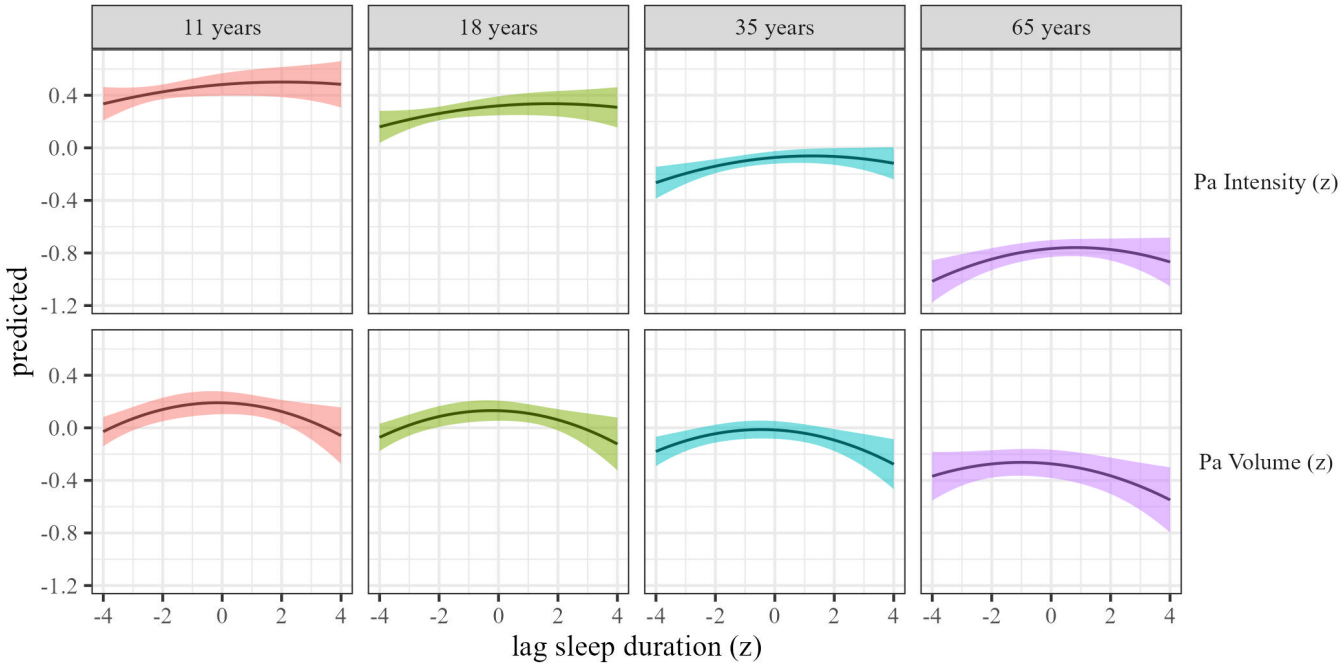

Figure 3. Physical activty by sleep duration

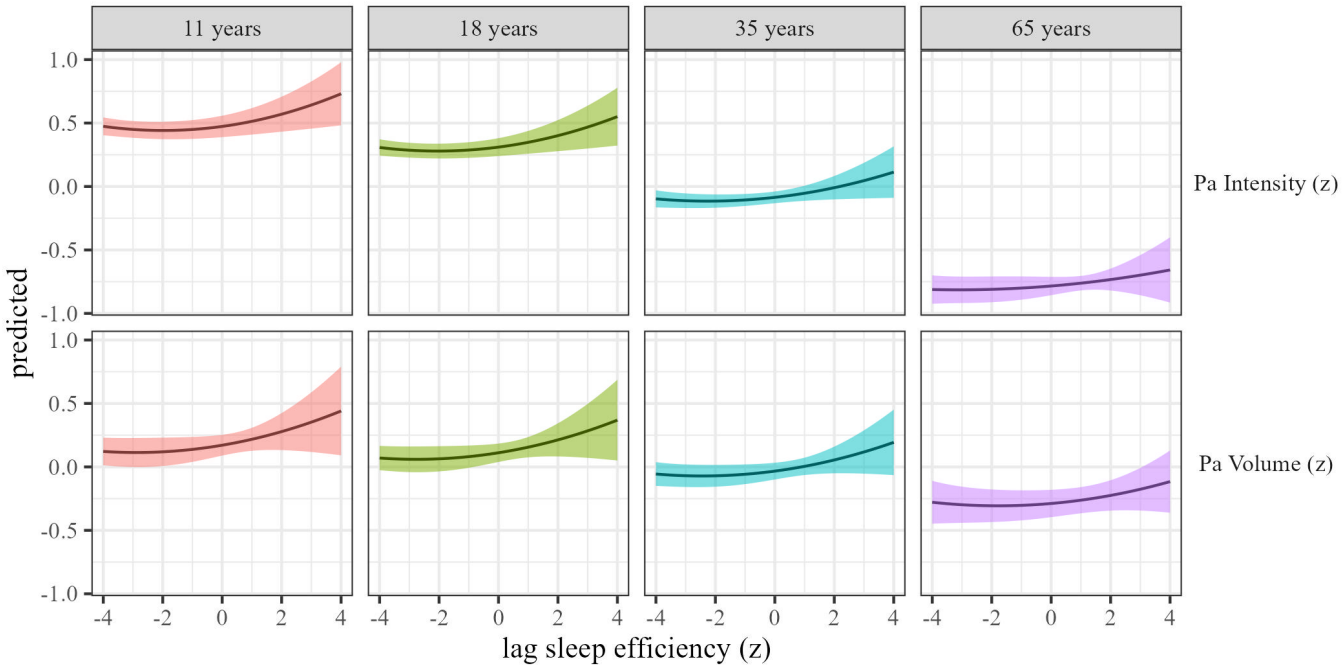

Figure 4. Physical activty by sleep efficiency

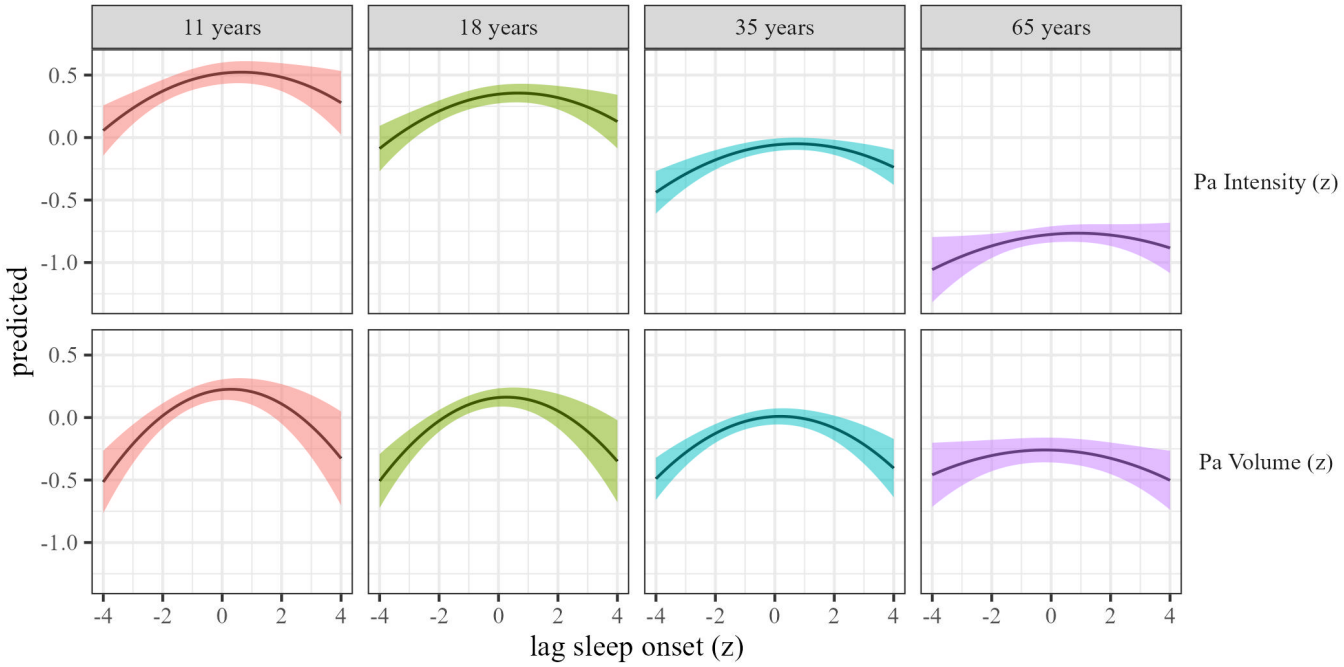

Figure 5. Physical activty by sleep onset

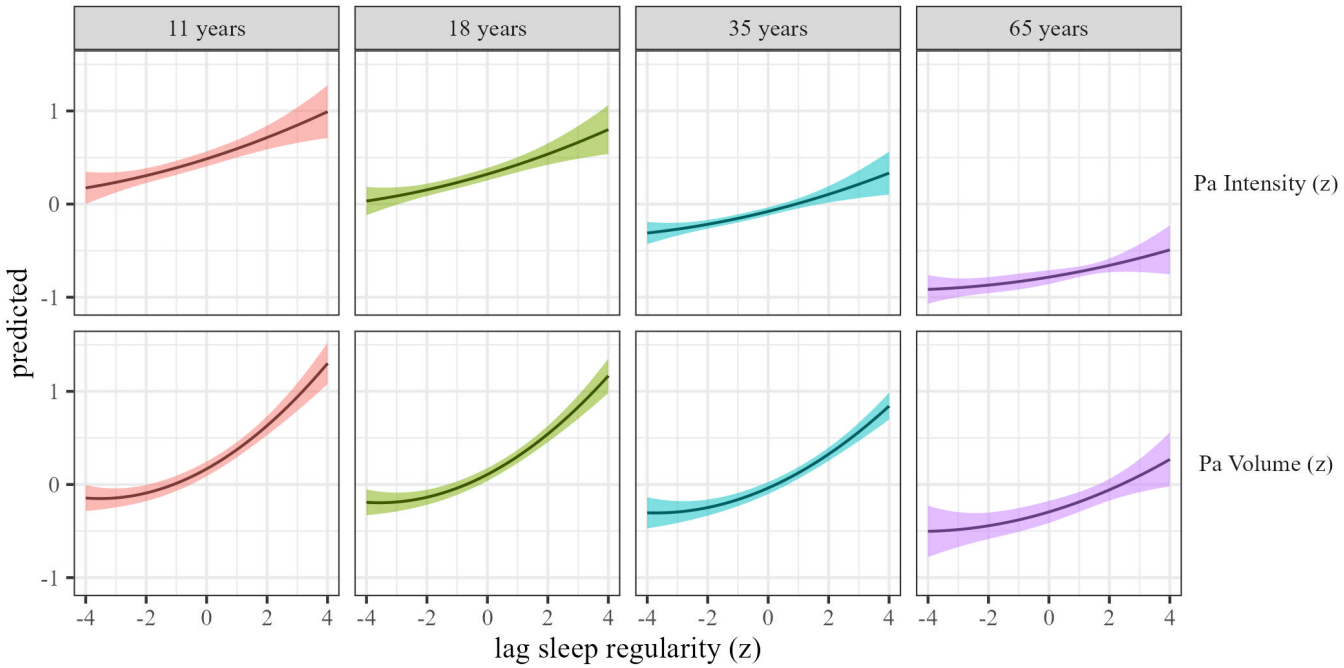

Figure 6. Physical activty by sleep regularity