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 193,318 observations of daily physical activity and sleep from 24,752 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	22.35 (2.90)
PA volume	39.49 (19.87)
PA intensity	-2.34 (0.31)
Sleep duration	406.69 (106.46)
Sleep efficiency	0.82 (0.11)
Sleep onset	22.53 (2.06)
Sleep regularity	55.02 (12.76)
Age	35.33 (28.36)
BMI	21.74 (5.92)
Accelerometer Wear Location	
Hip	8,813 (35.61%)
Wrist	15,939 (64.39%)
Region	
Africa	1,085 (4.38%)
Asia	730 (2.95%)
Europe	14,778 (59.70%)
North america	1,427 (5.77%)
Oceania	3,090 (12.48%)
South america	3,642 (14.71%)
Season	
Autumn	6,585 (26.60%)
Spring	7,651 (30.91%)
Summer	3,991 (16.12%)
Winter	6,525 (26.36%)
Sex	
Female	12,300 (49.69%)
Male	12,452 (50.31%)
Sleep Conditions Reported	
Yes	1,008 (4.07%)
Socioeconomic Status	
Low	8,293 (33.50%)
Medium	8,452 (34.15%)
High	8,007 (32.35%)

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

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

Term	β [95% CI]	SE	t	p
Sleep duration				
(Intercept)	0.76 [0.31, 1.20]	0.23	3.33	.071
Scale PA volume	-0.02 [-0.08, 0.04]	0.03	-0.61	.569
Age	-0.01 [-0.01, -0.01]	0.00	-4.68	.029
Scale PA volume^2	0.00 [-0.01, 0.01]	0.01	-0.15	.883
Scale PA volume:age	0.00 [0.00, 0.00]	0.00	1.50	.154
Age:scale PA volume^2	0.00 [0.00, 0.00]	0.00	0.60	.561
Sleep efficiency				
(Intercept)	-0.43 [-0.57, -0.28]	0.07	-5.81	.003
Scale PA volume	0.24 [0.20, 0.27]	0.02	13.52	$< .001$
Age	0.01 [0.01, 0.01]	0.00	11.93	$< .001$
Scale PA volume^2	-0.03 [-0.04, -0.02]	0.01	-5.46	$< .001$
Scale PA volume:age	0.00 [0.00, 0.00]	0.00	-7.27	$< .001$
Age:scale PA volume^2	0.00 [0.00, 0.00]	0.00	0.50	.626
Sleep onset				
(Intercept)	-0.94 [-1.13, -0.74]	0.10	-9.52	.003
Scale PA volume	0.14 [0.11, 0.17]	0.02	8.73	$< .001$
Age	0.02 [0.02, 0.02]	0.00	21.71	$< .001$
Scale PA volume^2	-0.02 [-0.03, -0.01]	0.00	-4.00	.001
Scale PA volume:age	0.00 [-0.01, 0.00]	0.00	-8.89	$< .001$
Age:scale PA volume^2	0.00 [0.00, 0.00]	0.00	1.89	.095
Sleep regularity				
(Intercept)	-0.13 [-0.45, 0.20]	0.17	-0.75	.522
Scale PA volume	0.33 [0.28, 0.38]	0.02	13.19	$< .001$
Age	0.00 [0.00, 0.01]	0.00	2.49	.110
Scale PA volume^2	-0.03 [-0.04, -0.02]	0.00	-6.41	$< .001$
Scale PA volume:age	0.00 [0.00, 0.00]	0.00	0.07	.945
Age:scale PA volume^2	0.00 [0.00, 0.00]	0.00	-3.21	.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)	0.71 [0.25, 1.17]	0.23	3.01	.086
Scale PA intensity	0.07 [-0.01, 0.16]	0.04	1.67	.165
Age	-0.01 [-0.01, 0.00]	0.00	-3.56	.056
Scale PA intensity^2	-0.01 [-0.04, 0.03]	0.02	-0.34	.735
Scale PA intensity:age	0.00 [0.00, 0.00]	0.00	-0.84	.441
Age:scale PA intensity^2	0.00 [0.00, 0.00]	0.00	-0.27	.793
Sleep efficiency				
(Intercept)	-0.51 [-0.66, -0.36]	0.08	-6.47	.002
Scale PA intensity	0.07 [0.02, 0.12]	0.02	2.95	.003
Age	0.01 [0.01, 0.01]	0.00	11.90	$< .001$
Scale PA intensity^2	0.02 [0.00, 0.05]	0.01	1.63	.105
Scale PA intensity:age	0.00 [0.00, 0.00]	0.00	-2.37	.019
Age:scale PA intensity^2	0.00 [0.00, 0.00]	0.00	-2.45	.016
Sleep onset				
(Intercept)	-0.91 [-1.10, -0.72]	0.10	-9.33	.002
Scale PA intensity	-0.03 [-0.11, 0.05]	0.04	-0.78	.488
Age	0.02 [0.01, 0.02]	0.00	13.37	.001
Scale PA intensity^2	-0.01 [-0.04, 0.02]	0.02	-0.48	.643
Scale PA intensity:age	0.00 [0.00, 0.00]	0.00	-0.39	.712
Age:scale PA intensity^2	0.00 [0.00, 0.00]	0.00	1.30	.215
Sleep regularity				
(Intercept)	-0.30 [-0.64, 0.03]	0.17	-1.77	.200
Scale PA intensity	0.28 [0.22, 0.34]	0.03	9.39	$< .001$
Age	0.01 [0.00, 0.01]	0.00	3.10	.062
Scale PA intensity^2	-0.05 [-0.08, -0.02]	0.02	-3.01	.004
Scale PA intensity:age	0.00 [0.00, 0.00]	0.00	-5.74	$< .001$
Age:scale PA intensity^2	0.00 [0.00, 0.00]	0.00	0.96	.340

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)	0.23 [0.04, 0.42]	0.10	2.33	.081
Scale sleep duration lag	0.00 [-0.02, 0.03]	0.01	0.26	.799
Age	-0.01 [-0.01, -0.01]	0.00	-7.56	.002
Scale sleep duration lag^2	-0.02 [-0.04, 0.00]	0.01	-2.31	.087
Scale sleep duration lag:age	0.00 [0.00, 0.00]	0.00	-0.88	.381
Age:scale sleep duration lag^2	0.00 [0.00, 0.00]	0.00	0.74	.488
PA intensity				
(Intercept)	0.81 [0.69, 0.92]	0.06	13.40	$< .001$
Scale sleep duration lag	0.00 [-0.04, 0.04]	0.02	-0.10	.928
Age	-0.02 [-0.03, -0.02]	0.00	-31.77	$< .001$
Scale sleep duration lag^2	0.00 [-0.01, 0.01]	0.01	-0.03	.978
Scale sleep duration lag:age	0.00 [0.00, 0.00]	0.00	1.05	.334
Age:scale sleep duration lag^2	0.00 [0.00, 0.00]	0.00	-0.67	.545

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)	0.20 [0.04, 0.37]	0.09	2.39	.063
Scale sleep efficiency lag	0.04 [0.00, 0.09]	0.02	1.98	.103
Age	-0.01 [-0.01, -0.01]	0.00	-8.00	.001
Scale sleep efficiency lag^2	0.00 [-0.01, 0.01]	0.01	0.36	.736
Scale sleep efficiency lag:age	0.00 [0.00, 0.00]	0.00	-0.78	.436
Age:scale sleep efficiency lag^2	0.00 [0.00, 0.00]	0.00	0.51	.631
PA intensity				
(Intercept)	0.80 [0.70, 0.91]	0.06	14.47	$< .001$
Scale sleep efficiency lag	0.03 [0.00, 0.07]	0.02	1.79	.111
Age	-0.02 [-0.03, -0.02]	0.00	-26.55	$< .001$
Scale sleep efficiency lag^2	0.01 [-0.01, 0.02]	0.01	0.97	.391
Scale sleep efficiency lag:age	0.00 [0.00, 0.00]	0.00	0.12	.906
Age:scale sleep efficiency lag^2	0.00 [0.00, 0.00]	0.00	0.20	.849

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)	0.29 [0.13, 0.45]	0.08	3.49	.015
Scale sleep onset lag	0.06 [0.00, 0.12]	0.03	1.96	.129
Age	-0.01 [-0.01, -0.01]	0.00	-8.12	.001
Scale sleep onset lag^2	-0.05 [-0.08, -0.02]	0.02	-3.53	.019
Scale sleep onset lag:age	0.00 [0.00, 0.00]	0.00	-2.02	.093
Age:scale sleep onset lag^2	0.00 [0.00, 0.00]	0.00	2.34	.036
PA intensity				
(Intercept)	0.84 [0.73, 0.95]	0.05	15.27	$< .001$
Scale sleep onset lag	0.02 [-0.02, 0.06]	0.02	0.92	.383
Age	-0.03 [-0.03, -0.02]	0.00	-25.76	$< .001$
Scale sleep onset lag^2	-0.03 [-0.05, 0.00]	0.01	-2.21	.051
Scale sleep onset lag:age	0.00 [0.00, 0.00]	0.00	-0.50	.620
Age:scale sleep onset lag^2	0.00 [0.00, 0.00]	0.00	1.60	.115

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)	0.18 [0.02, 0.35]	0.08	2.26	.073
Scale sleep regularity lag	0.21 [0.17, 0.24]	0.02	11.49	< .001
Age	-0.01 [-0.01, -0.01]	0.00	-7.76	.002
Scale sleep regularity lag^2	0.03 [0.01, 0.04]	0.01	4.16	< .001
Scale sleep regularity lag:age	0.00 [0.00, 0.00]	0.00	-5.05	.002
Age:scale sleep regularity lag^2	0.00 [0.00, 0.00]	0.00	-1.20	.234
PA intensity				
(Intercept)	0.80 [0.70, 0.91]	0.05	15.72	< .001
Scale sleep regularity lag	0.12 [0.09, 0.14]	0.01	8.73	< .001
Age	-0.02 [-0.03, -0.02]	0.00	-26.72	< .001
Scale sleep regularity lag^2	0.01 [-0.01, 0.02]	0.01	0.89	.400
Scale sleep regularity lag:age	0.00 [0.00, 0.00]	0.00	-2.96	.018
Age:scale sleep regularity lag^2	0.00 [0.00, 0.00]	0.00	-0.38	.713

Note. Adjusted for SES, BMI, and sex.

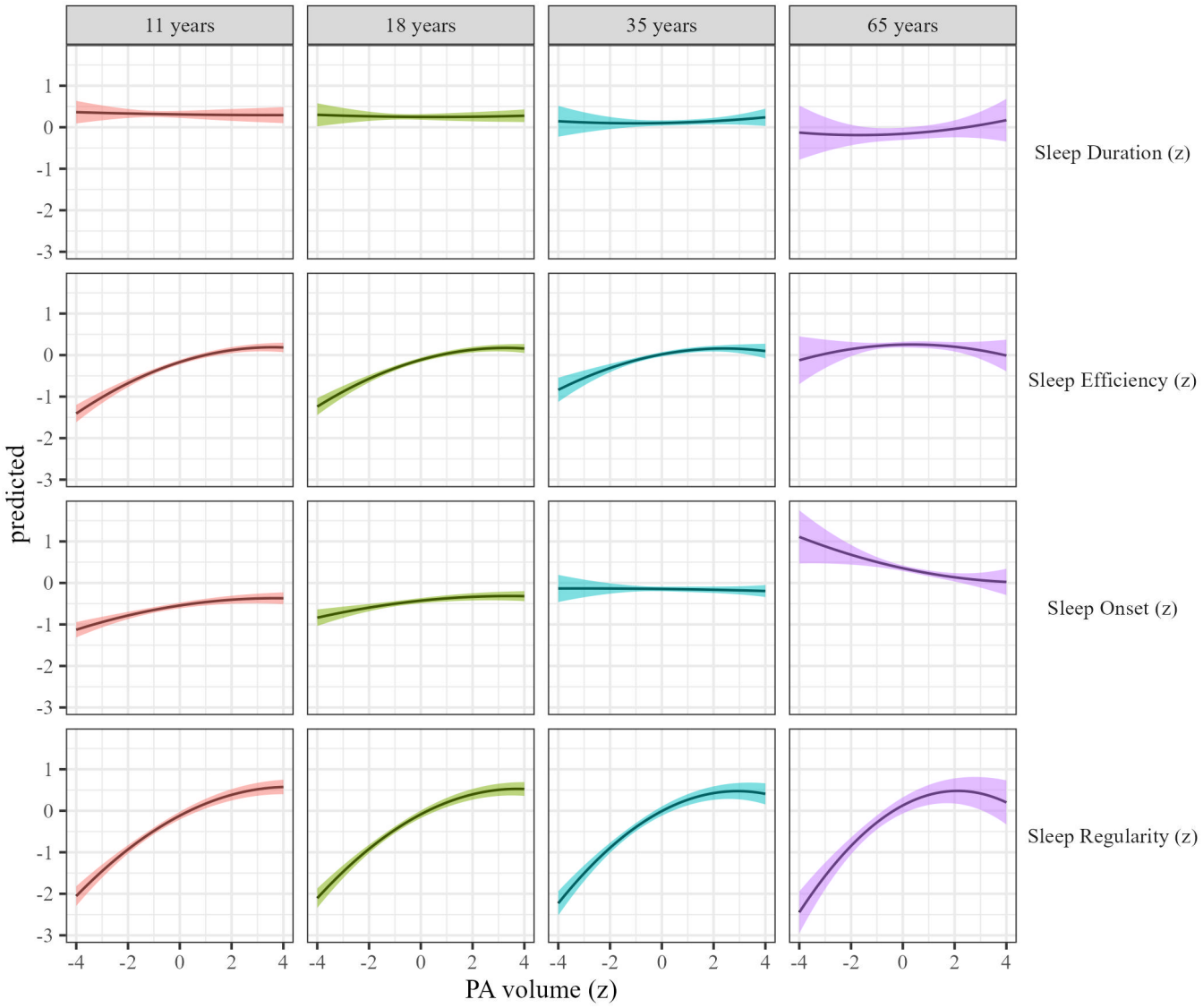

Figure 1. Sleep metrics on Physical activity volume

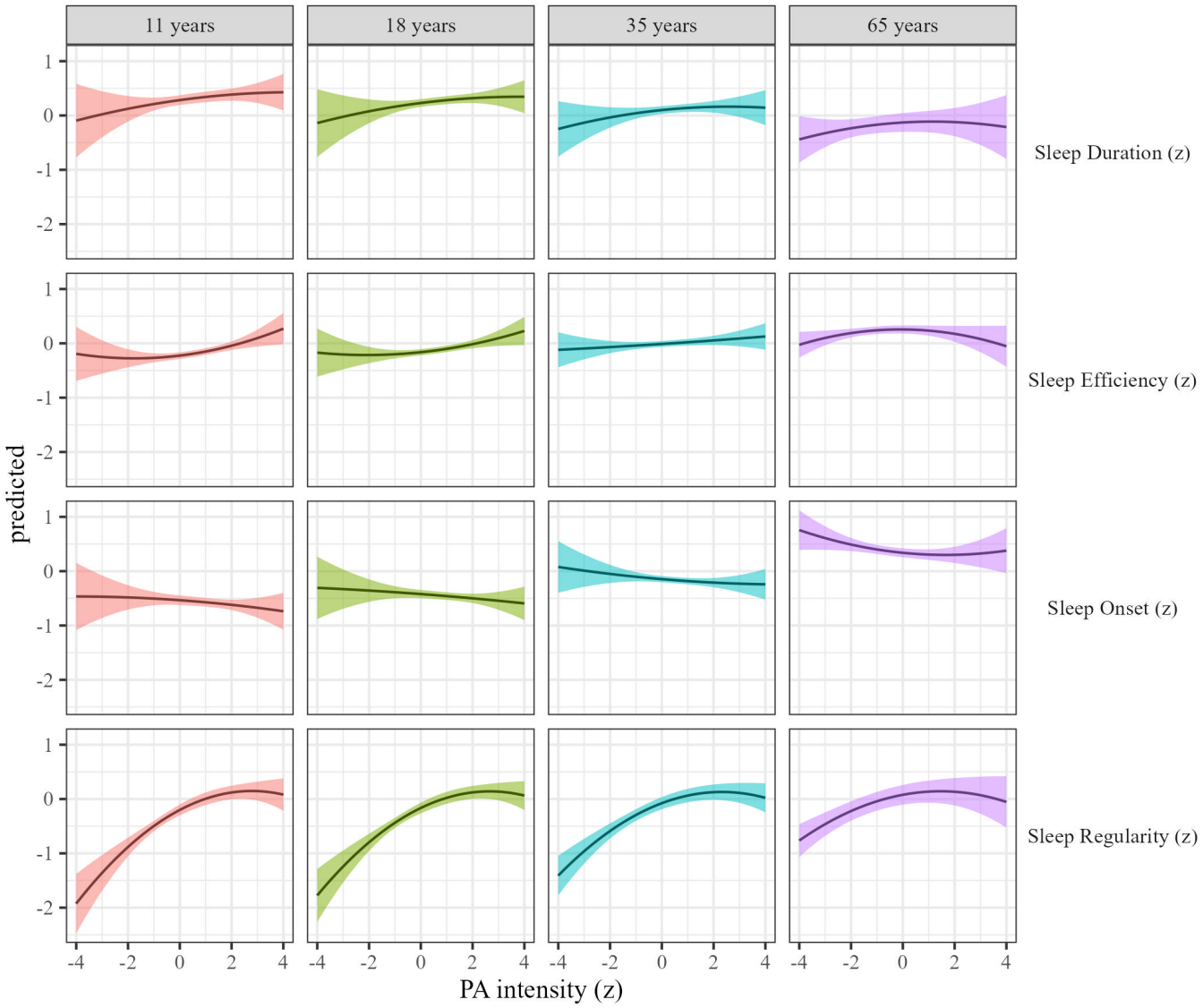

Figure 2. Sleep metrics on Physical activity intensity

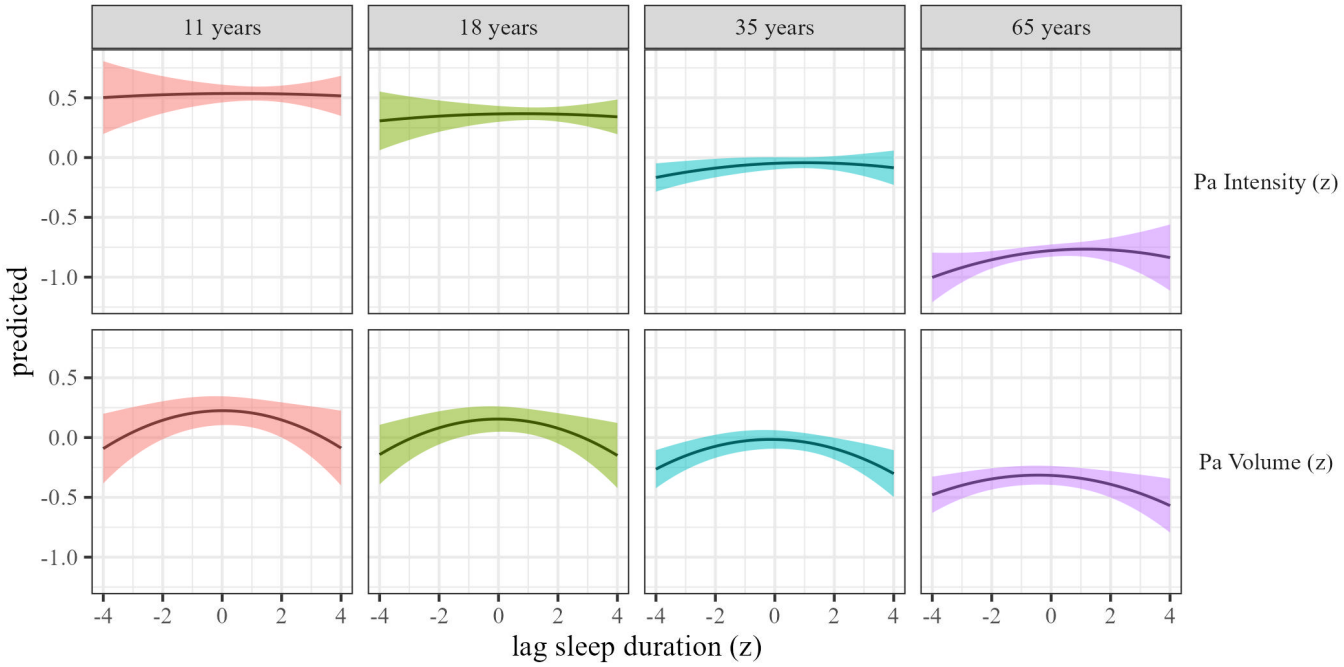

Figure 3. Physical activty by sleep duration

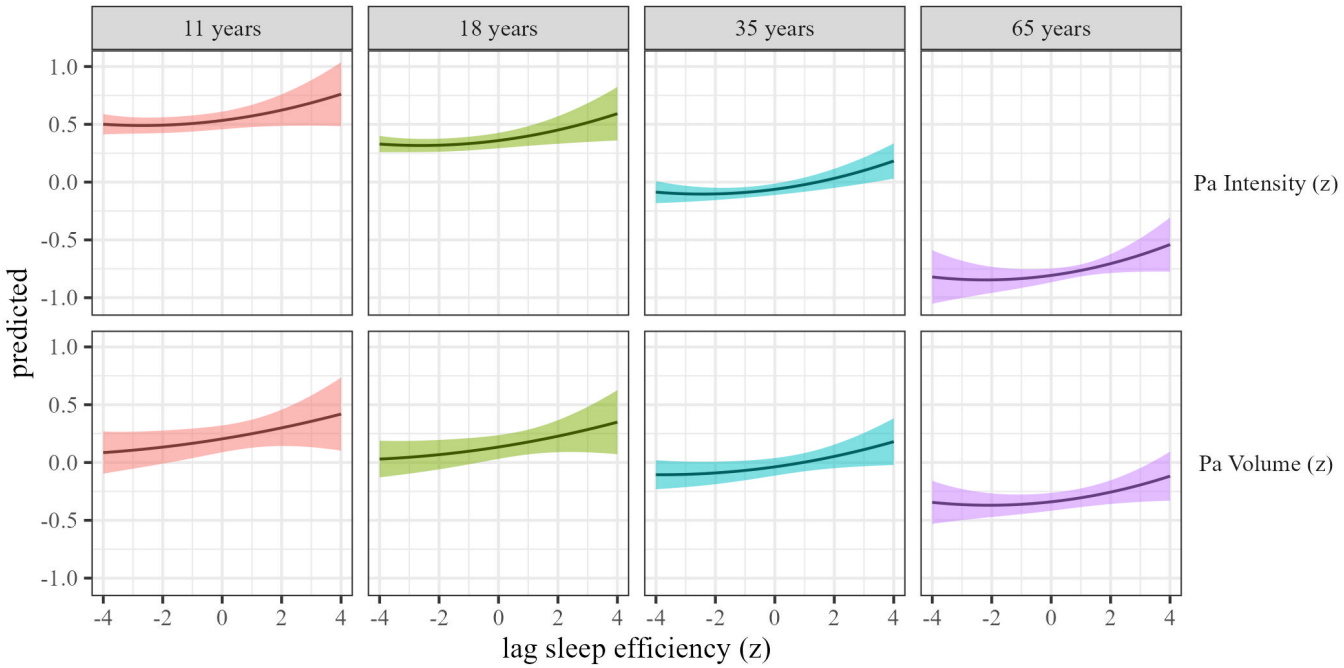

Figure 4. Physical activty by sleep efficiency

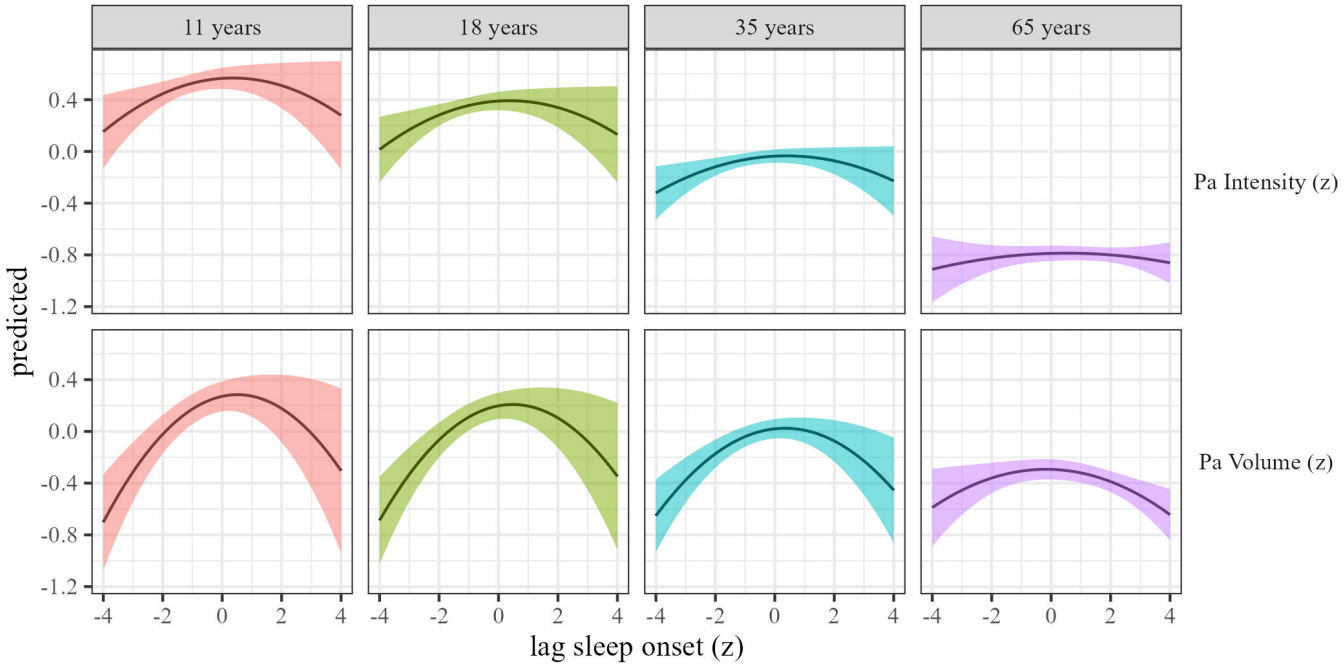

Figure 5. Physical activty by sleep onset

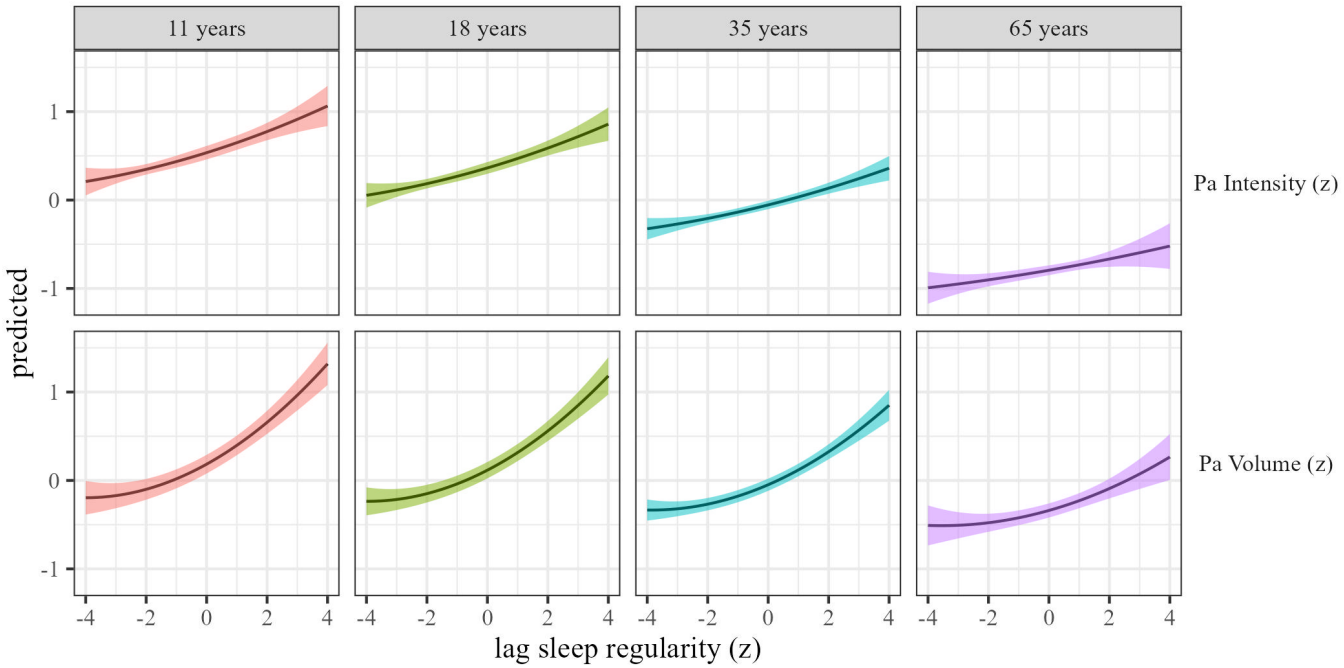

Figure 6. Physical activty by sleep regularity