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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. 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*

| Characteristic              | Age group       |                 |                 |                 |                 |
|-----------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|
|                             | 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           |
| Valid weartime hours        | 21.77 (3.03)    | 21.20 (3.97)    | 21.06 (3.46)    | 22.57 (2.49)    | 23.78 (1.03)    |
| PA volume                   | 43.68 (25.56)   | 42.28 (16.83)   | 41.37 (11.44)   | 39.80 (13.35)   | 31.23 (10.39)   |
| PA intensity                | -2.11 (0.19)    | -2.20 (0.19)    | -2.35 (0.20)    | -2.50 (0.19)    | -2.67 (0.22)    |
| 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)   |
| Age                         | 9.58 (1.36)     | 13.73 (2.40)    | 22.56 (6.04)    | 57.77 (6.91)    | 72.22 (4.74)    |
| BMI                         | 17.98 (3.31)    | 20.08 (5.30)    | 24.79 (5.94)    | 26.99 (4.92)    | 27.08 (4.41)    |
| 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%) |
| 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%)  |
| 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%)  |

Table 1 continued

| Characteristic            | Age group      |                |              |                |                |
|---------------------------|----------------|----------------|--------------|----------------|----------------|
|                           | 2-11 years     | 12-18 years    | 19-35 years  | 36-65 years    | 66+ years      |
| 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

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

| Term                             | $\beta$ [95% CI]     | SE   | t      | p      |
|----------------------------------|----------------------|------|--------|--------|
| Sleep duration                   |                      |      |        |        |
| (Intercept)                      | 0.64 [0.54, 0.74]    | 0.05 | 12.27  | < .001 |
| Scale PA volume                  | -0.01 [-0.05, 0.03]  | 0.02 | -0.46  | .645   |
| Age                              | -0.01 [-0.01, -0.01] | 0.00 | -10.38 | < .001 |
| Scale PA volume <sup>2</sup>     | 0.00 [-0.01, 0.02]   | 0.01 | 0.53   | .608   |
| Scale PA volume:age              | 0.00 [0.00, 0.00]    | 0.00 | 1.57   | .120   |
| Age:scale PA volume <sup>2</sup> | 0.00 [0.00, 0.00]    | 0.00 | -0.22  | .836   |
| Sleep efficiency                 |                      |      |        |        |
| (Intercept)                      | -0.31 [-0.41, -0.20] | 0.05 | -5.85  | < .001 |
| Scale PA volume                  | 0.23 [0.20, 0.27]    | 0.02 | 13.43  | < .001 |
| Age                              | 0.01 [0.01, 0.01]    | 0.00 | 16.59  | < .001 |
| Scale PA volume <sup>2</sup>     | -0.03 [-0.04, -0.02] | 0.00 | -5.73  | < .001 |
| Scale PA volume:age              | 0.00 [0.00, 0.00]    | 0.00 | -7.55  | < .001 |
| Age:scale PA volume <sup>2</sup> | 0.00 [0.00, 0.00]    | 0.00 | 0.13   | .895   |
| Sleep onset                      |                      |      |        |        |
| (Intercept)                      | -0.96 [-1.05, -0.87] | 0.05 | -20.78 | < .001 |
| Scale PA volume                  | 0.13 [0.10, 0.16]    | 0.02 | 7.95   | < .001 |
| Age                              | 0.02 [0.02, 0.02]    | 0.00 | 23.18  | < .001 |
| Scale PA volume <sup>2</sup>     | -0.02 [-0.03, -0.01] | 0.00 | -4.04  | .001   |
| Scale PA volume:age              | 0.00 [0.00, 0.00]    | 0.00 | -10.18 | < .001 |
| Age:scale PA volume <sup>2</sup> | 0.00 [0.00, 0.00]    | 0.00 | 1.89   | .125   |
| Sleep regularity                 |                      |      |        |        |
| (Intercept)                      | 0.14 [0.04, 0.24]    | 0.05 | 2.73   | .007   |
| Scale PA volume                  | 0.33 [0.29, 0.38]    | 0.02 | 14.10  | < .001 |
| Age                              | 0.01 [0.01, 0.01]    | 0.00 | 10.34  | < .001 |
| Scale PA volume <sup>2</sup>     | -0.03 [-0.04, -0.02] | 0.01 | -5.73  | < .001 |
| Scale PA volume:age              | 0.00 [0.00, 0.00]    | 0.00 | -0.33  | .751   |
| Age:scale PA volume <sup>2</sup> | 0.00 [0.00, 0.00]    | 0.00 | -1.80  | .147   |

*Note.* Adjusted for SES, BMI, and sex.



Table 3

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

| Term                                | $\beta$ [95% CI]     | SE   | t      | p      |
|-------------------------------------|----------------------|------|--------|--------|
| Sleep duration                      |                      |      |        |        |
| (Intercept)                         | 0.58 [0.47, 0.69]    | 0.06 | 10.45  | < .001 |
| Scale PA intensity                  | 0.10 [0.04, 0.15]    | 0.03 | 3.39   | .002   |
| Age                                 | -0.01 [-0.01, -0.01] | 0.00 | -12.17 | < .001 |
| Scale PA intensity <sup>2</sup>     | -0.01 [-0.04, 0.03]  | 0.02 | -0.35  | .726   |
| Scale PA intensity:age              | 0.00 [0.00, 0.00]    | 0.00 | -1.83  | .094   |
| Age:scale PA intensity <sup>2</sup> | 0.00 [0.00, 0.00]    | 0.00 | -0.33  | .740   |
| Sleep efficiency                    |                      |      |        |        |
| (Intercept)                         | -0.37 [-0.48, -0.26] | 0.06 | -6.71  | < .001 |
| Scale PA intensity                  | 0.07 [0.01, 0.12]    | 0.03 | 2.19   | .050   |
| Age                                 | 0.01 [0.01, 0.01]    | 0.00 | 17.17  | < .001 |
| Scale PA intensity <sup>2</sup>     | 0.02 [-0.02, 0.06]   | 0.02 | 0.78   | .464   |
| Scale PA intensity:age              | 0.00 [0.00, 0.00]    | 0.00 | -2.06  | .048   |
| Age:scale PA intensity <sup>2</sup> | 0.00 [0.00, 0.00]    | 0.00 | -1.56  | .145   |
| Sleep onset                         |                      |      |        |        |
| (Intercept)                         | -0.93 [-1.02, -0.84] | 0.05 | -19.80 | < .001 |
| Scale PA intensity                  | -0.05 [-0.09, -0.01] | 0.02 | -2.66  | .008   |
| Age                                 | 0.02 [0.01, 0.02]    | 0.00 | 26.44  | < .001 |
| Scale PA intensity <sup>2</sup>     | -0.01 [-0.03, 0.02]  | 0.01 | -0.48  | .634   |
| Scale PA intensity:age              | 0.00 [0.00, 0.00]    | 0.00 | 0.19   | .848   |
| Age:scale PA intensity <sup>2</sup> | 0.00 [0.00, 0.00]    | 0.00 | 1.22   | .236   |
| Sleep regularity                    |                      |      |        |        |
| (Intercept)                         | 0.04 [-0.07, 0.14]   | 0.05 | 0.73   | .466   |
| Scale PA intensity                  | 0.28 [0.23, 0.34]    | 0.03 | 9.70   | < .001 |
| Age                                 | 0.01 [0.01, 0.01]    | 0.00 | 11.57  | < .001 |
| Scale PA intensity <sup>2</sup>     | -0.05 [-0.08, -0.02] | 0.01 | -3.58  | < .001 |
| Scale PA intensity:age              | 0.00 [0.00, 0.00]    | 0.00 | -5.24  | < .001 |
| Age:scale PA intensity <sup>2</sup> | 0.00 [0.00, 0.00]    | 0.00 | 1.09   | .288   |

*Note.* Adjusted for SES, BMI, and sex.

Table 4

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

| Term                                      | $\beta$ [95% CI]     | SE   | t      | p      |
|---|----------------------|------|--------|--------|
| PA volume                                 |                      |      |        |        |
| (Intercept)                               | 0.39 [0.27, 0.50]    | 0.06 | 6.72   | < .001 |
| Scale sleep duration lag                  | 0.02 [-0.01, 0.05]   | 0.02 | 1.09   | .302   |
| Age                                       | -0.01 [-0.01, -0.01] | 0.00 | -11.64 | < .001 |
| Scale sleep duration lag <sup>2</sup>     | -0.01 [-0.03, 0.00]  | 0.01 | -2.15  | .058   |
| Scale sleep duration lag:age              | 0.00 [0.00, 0.00]    | 0.00 | -1.74  | .090   |
| Age:scale sleep duration lag <sup>2</sup> | 0.00 [0.00, 0.00]    | 0.00 | 0.32   | .749   |
| PA intensity                              |                      |      |        |        |
| (Intercept)                               | 1.00 [0.91, 1.08]    | 0.04 | 22.79  | < .001 |
| Scale sleep duration lag                  | 0.01 [-0.02, 0.04]   | 0.01 | 0.73   | .490   |
| Age                                       | -0.02 [-0.02, -0.02] | 0.00 | -49.35 | < .001 |
| Scale sleep duration lag <sup>2</sup>     | 0.01 [0.00, 0.02]    | 0.01 | 1.13   | .277   |
| Scale sleep duration lag:age              | 0.00 [0.00, 0.00]    | 0.00 | -0.07  | .945   |
| Age:scale sleep duration lag <sup>2</sup> | 0.00 [0.00, 0.00]    | 0.00 | -2.49  | .013   |

*Note.* Adjusted for SES, BMI, and sex.

Table 5

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

| Term  | $\beta$ [95% CI]     | SE   | t      | p      |
|---|----------------------|------|--------|--------|
| PA volume                                   |                      |      |        |        |
| (Intercept)                                 | 0.38 [0.25, 0.50]    | 0.06 | 5.96   | < .001 |
| Scale sleep efficiency lag                  | 0.06 [0.02, 0.10]    | 0.02 | 3.28   | .008   |
| Age   | -0.01 [-0.01, -0.01] | 0.00 | -12.55 | < .001 |
| Scale sleep efficiency lag <sup>2</sup>     | 0.01 [0.00, 0.01]    | 0.00 | 1.93   | .054   |
| Scale sleep efficiency lag:age              | 0.00 [0.00, 0.00]    | 0.00 | -1.64  | .137   |
| Age:scale sleep efficiency lag <sup>2</sup> | 0.00 [0.00, 0.00]    | 0.00 | -0.96  | .343   |
| PA intensity                                |                      |      |        |        |
| (Intercept)                                 | 1.02 [0.93, 1.10]    | 0.04 | 23.69  | < .001 |
| Scale sleep efficiency lag                  | 0.05 [0.03, 0.08]    | 0.01 | 3.85   | < .001 |
| Age   | -0.02 [-0.02, -0.02] | 0.00 | -53.82 | < .001 |
| Scale sleep efficiency lag <sup>2</sup>     | 0.01 [0.00, 0.02]    | 0.00 | 2.62   | .018   |
| Scale sleep efficiency lag:age              | 0.00 [0.00, 0.00]    | 0.00 | -1.81  | .090   |
| Age:scale sleep efficiency lag <sup>2</sup> | 0.00 [0.00, 0.00]    | 0.00 | -1.73  | .090   |

*Note.* Adjusted for SES, BMI, and sex.

Table 6

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

| Term                                   | $\beta$ [95% CI]     | SE   | t      | p      |
|--|----------------------|------|--------|--------|
| PA volume                              |                      |      |        |        |
| (Intercept)                            | 0.43 [0.31, 0.54]    | 0.06 | 7.42   | < .001 |
| Scale sleep onset lag                  | 0.03 [-0.01, 0.07]   | 0.02 | 1.62   | .118   |
| Age                                    | -0.01 [-0.01, -0.01] | 0.00 | -10.74 | < .001 |
| Scale sleep onset lag <sup>2</sup>     | -0.05 [-0.08, -0.01] | 0.02 | -2.79  | .057   |
| Scale sleep onset lag:age              | 0.00 [0.00, 0.00]    | 0.00 | -1.29  | .250   |
| Age:scale sleep onset lag <sup>2</sup> | 0.00 [0.00, 0.00]    | 0.00 | 2.04   | .095   |
| PA intensity                           |                      |      |        |        |
| (Intercept)                            | 1.05 [0.95, 1.15]    | 0.05 | 20.40  | < .001 |
| Scale sleep onset lag                  | 0.02 [-0.01, 0.06]   | 0.02 | 1.25   | .243   |
| Age                                    | -0.02 [-0.02, -0.02] | 0.00 | -44.49 | < .001 |
| Scale sleep onset lag <sup>2</sup>     | -0.02 [-0.04, 0.01]  | 0.01 | -1.38  | .211   |
| Scale sleep onset lag:age              | 0.00 [0.00, 0.00]    | 0.00 | -0.55  | .585   |
| Age:scale sleep onset lag <sup>2</sup> | 0.00 [0.00, 0.00]    | 0.00 | 0.82   | .426   |

*Note.* Adjusted for SES, BMI, and sex.

Table 7

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

| Term  | $\beta$ [95% CI]     | SE   | t      | p      |
|---|----------------------|------|--------|--------|
| PA volume                                   |                      |      |        |        |
| (Intercept)                                 | 0.33 [0.21, 0.45]    | 0.06 | 5.37   | < .001 |
| Scale sleep regularity lag                  | 0.21 [0.18, 0.23]    | 0.01 | 15.61  | < .001 |
| Age   | -0.01 [-0.01, -0.01] | 0.00 | -13.58 | < .001 |
| Scale sleep regularity lag <sup>2</sup>     | 0.02 [0.01, 0.04]    | 0.01 | 2.55   | .037   |
| Scale sleep regularity lag:age              | 0.00 [0.00, 0.00]    | 0.00 | -5.33  | .001   |
| Age:scale sleep regularity lag <sup>2</sup> | 0.00 [0.00, 0.00]    | 0.00 | -1.01  | .363   |
| PA intensity                                |                      |      |        |        |
| (Intercept)                                 | 1.01 [0.92, 1.09]    | 0.04 | 22.99  | < .001 |
| Scale sleep regularity lag                  | 0.12 [0.09, 0.14]    | 0.01 | 10.06  | < .001 |
| Age   | -0.02 [-0.02, -0.02] | 0.00 | -52.55 | < .001 |
| Scale sleep regularity lag <sup>2</sup>     | 0.00 [-0.01, 0.01]   | 0.01 | 0.17   | .869   |
| Scale sleep regularity lag:age              | 0.00 [0.00, 0.00]    | 0.00 | -4.34  | < .001 |
| Age:scale sleep regularity lag <sup>2</sup> | 0.00 [0.00, 0.00]    | 0.00 | 0.02   | .982   |

*Note.* Adjusted for SES, BMI, and sex.

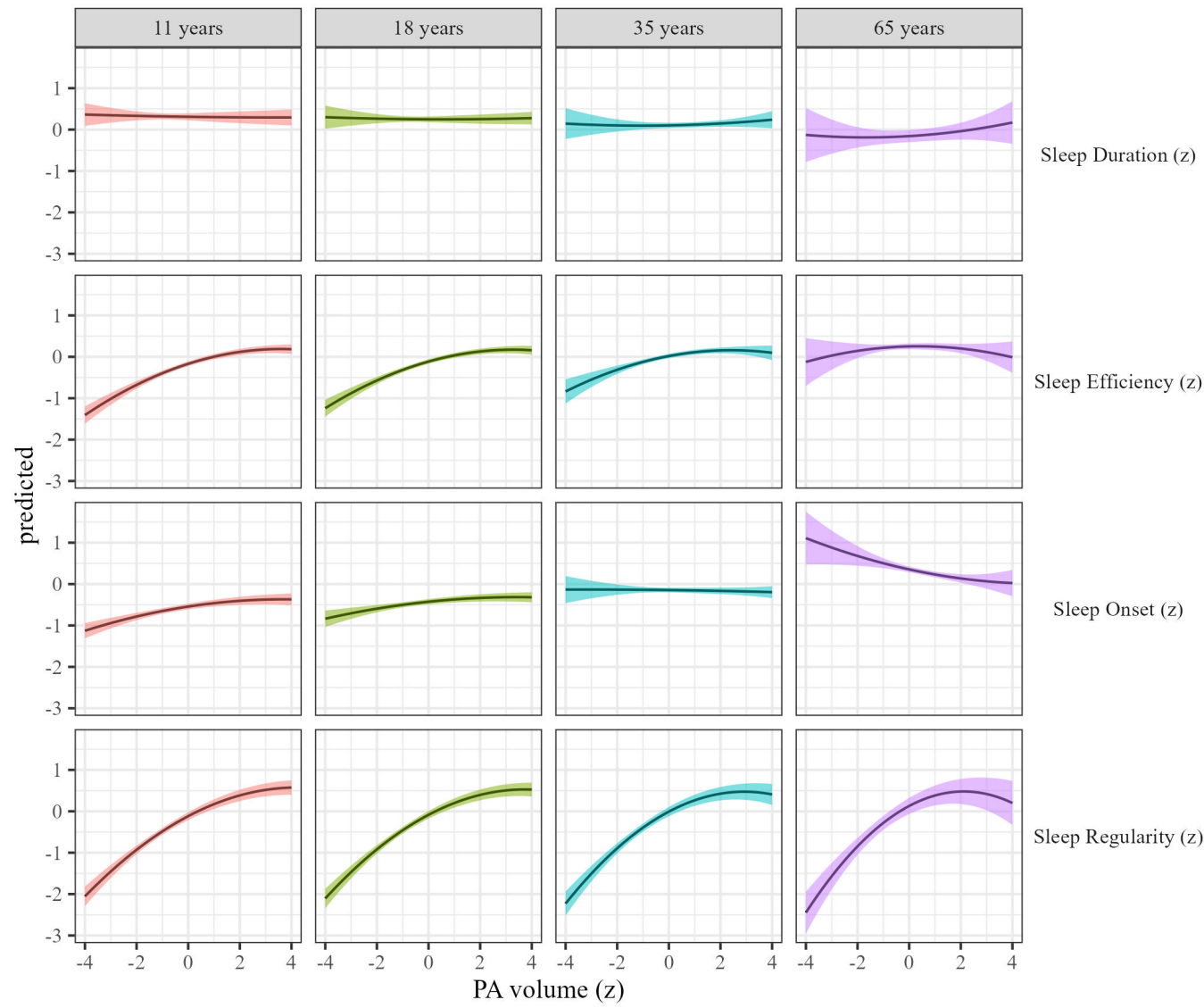


Figure 1. Sleep metrics on Physical activity volume

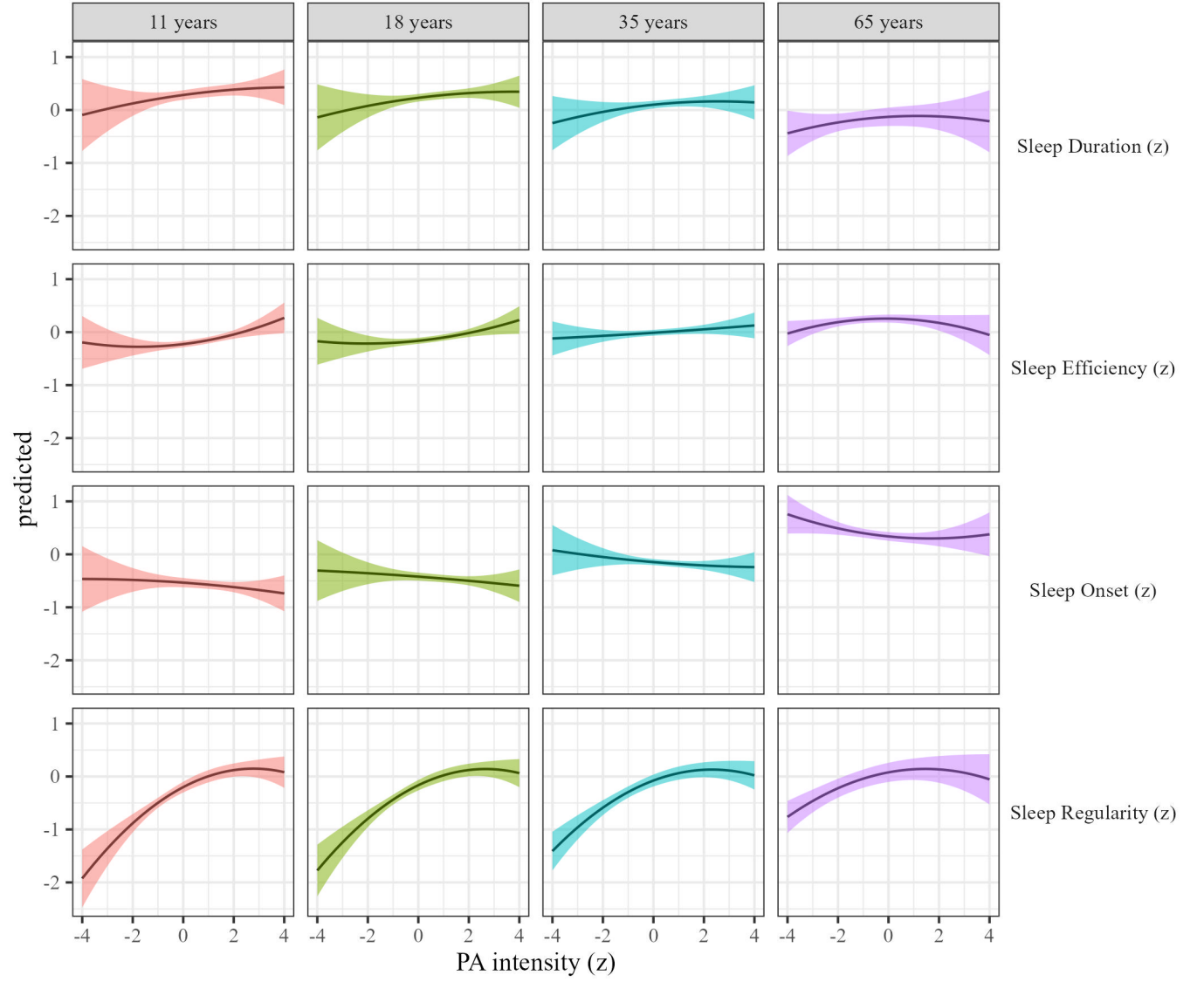


Figure 2. Sleep metrics on Physical activity intensity

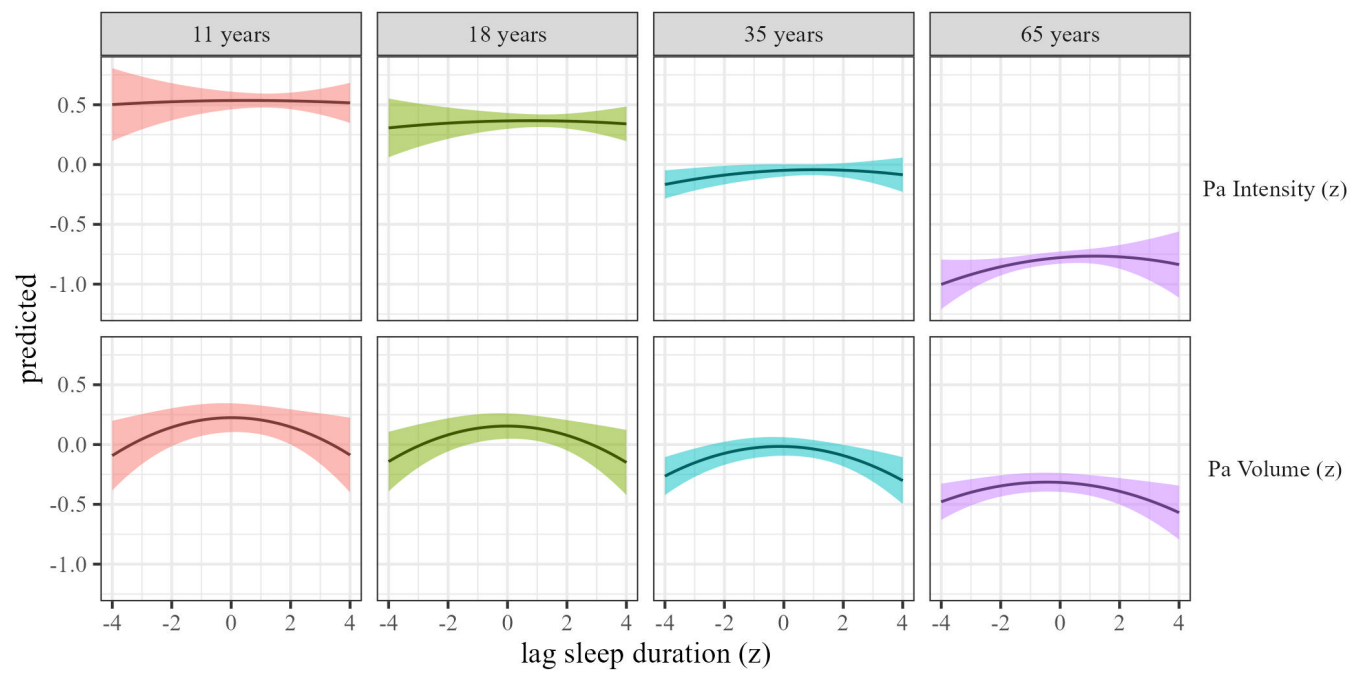


Figure 3. Physical activity by sleep duration

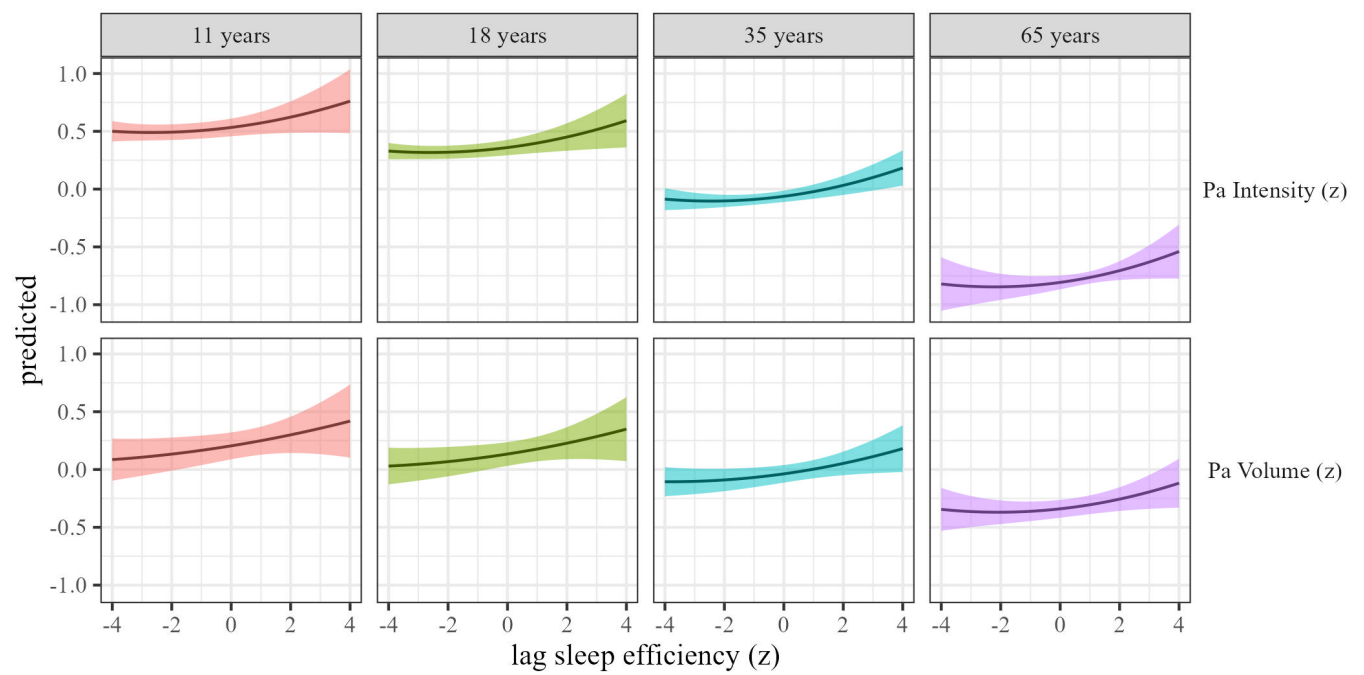


Figure 4. Physical activity by sleep efficiency



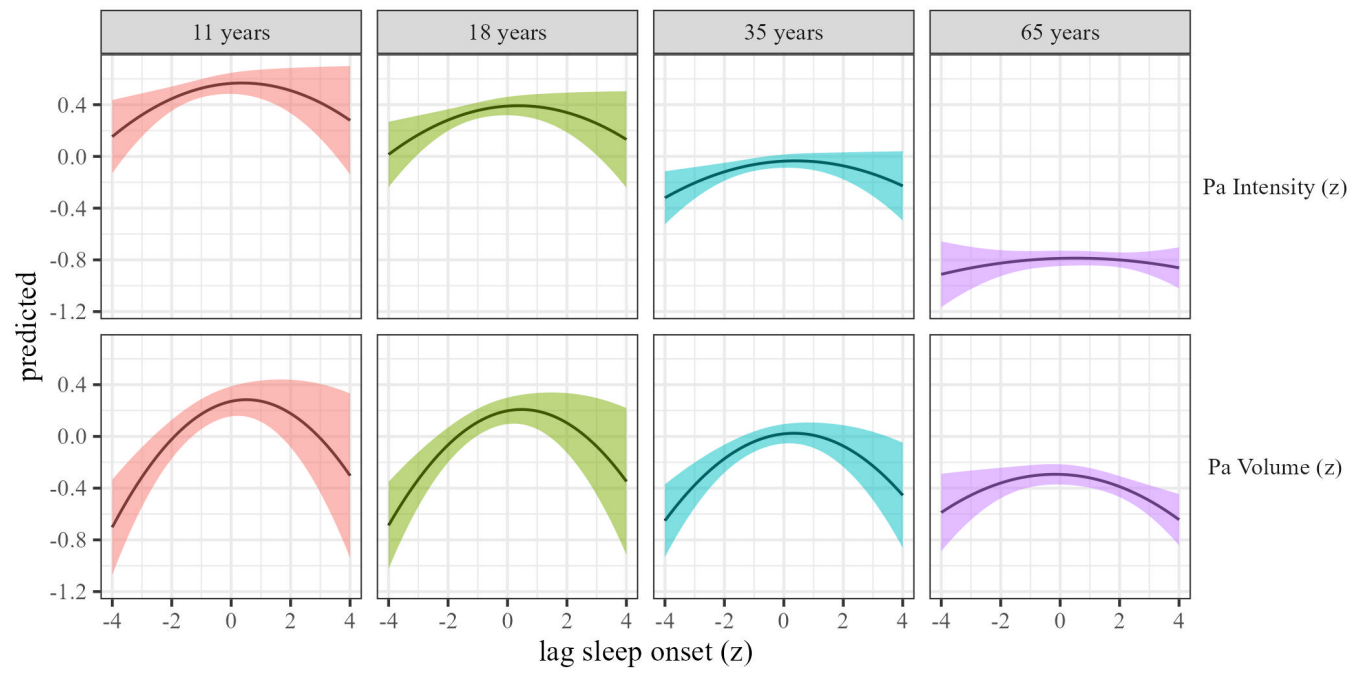


Figure 5. Physical activity by sleep onset

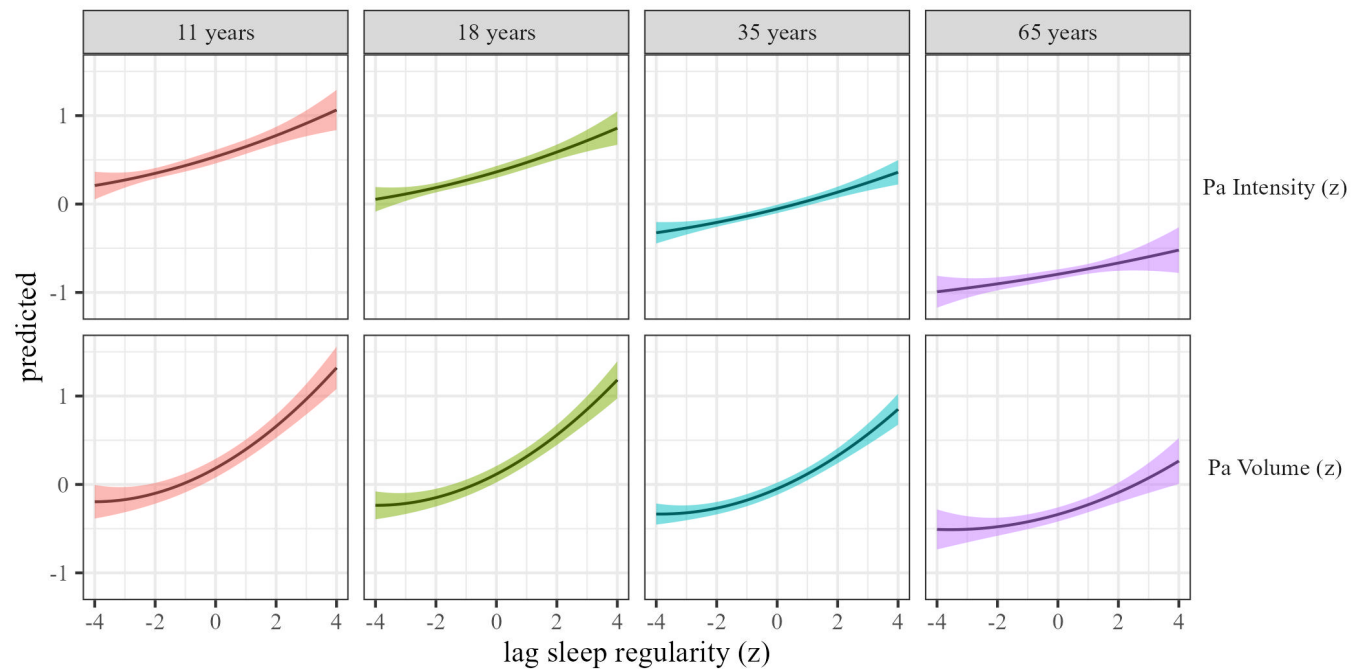


Figure 6. Physical activity by sleep regularity