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4- and 11-part 24-hour movement behaviour compositions for internalising and externalising problems in children and adolescents – Results from the MoMo 2.0-Study

Janis Fiedler

janis.fiedler@kit.edu

Karlsruhe Institute of Technology

Leon Klos

Karlsruhe Institute of Technology

Gareth Stratton

Manchester Metropolitan University

Alexander Woll

Karlsruhe Institute of Technology

Nils Swindell

Manchester Metropolitan University

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Abstract

Background

Children's and adolescents' movement behaviours across the 24-hour day are increasingly recognized as important for mental health. However, its relationship beyond broad intensity categories remain unclear. This study aims to examine how 4- and 11-part 24-hour movement behaviour compositions are associated with internalising and externalising problems in children and adolescents.

Methods

Cross-sectional 24-hour movement behaviour data from 2,642 children and adolescents of the MoMo 2.0-Study were collected via activPAL4 accelerometers over seven days and processed with ActiPASS to classify four intensity categories and eleven behaviours. Internalising and externalising problems were assessed with the German Strengths and Difficulties Questionnaire. Stratified by age group (4–10 vs. 11–17 years), compositional data analysis modelled daily time use as isometric log-ratio (ilr) coordinates. Associations were tested with ANOVAs, followed by isotemporal substitution analyses.

Results

Valid data of 1,522 participants (52.0% girls) was analysed. Four-part composition models showed significant ilr main effects for internalising problems in both children ($p < 0.001$, $\eta^2 = 0.021$) and adolescents ($p = 0.013$, $\eta^2 = 0.016$), but not for externalising porblems in either group. In children, reallocating time to moderate-to-vigorous physical activity or sleep was associated with lower internalising scores; in adolescents, sedentary-to-light physical activity reallocations showed the strongest associations. For the 11-part composition, significant ilr main effects were observed for internalising problems ($p = 0.002$, $\eta^2 = 0.033$), but not for externalising problems in children. Among adolescents, significant ilr main effects were found for both internalising ($p = 0.001$, $\eta^2 = 0.044$) and externalising problems ($p < 0.001$, $\eta^2 = 0.046$). Replacing 10 minutes of running with cycling or slow walking corresponded to a clinically relevant 1-point internalising score increase in children. In adolescents, reallocating from slow walking or moving to standing was associated with fewer externalising problems.

Conclusions

The granularity of movement behaviour classification influences associations with youth mental health. Internalising symptoms related to the 24-hour behaviour composition regardless of granularity, while externalising symptoms were associated with behaviour only at finer granularity in adolescents. Fine-

grained analysis reveals associations hidden by broad categories and can inform activity-specific recommendations.

Background

Mental health disorders are a leading cause of ill health and disability with one in seven young people aged 10–19 years suffering from depression, anxiety, or behavioural difficulties (1). Further, the 2011 Global Burden of Disease Study (2) reported an 11.8% annual increase in new cases of mental disorders during the COVID-19 pandemic, with anxiety disorders and depression in the top four causes of nonfatal disability (3).

In Germany, the COPSY longitudinal study (4) reported an increase in mental health problems from 18% to 30% before and during the COVID-19 pandemic, respectively, remaining at a higher-than pre-pandemic level thereafter. Further, global data indicate that elevated mental health difficulties have persisted well beyond the immediate impact of the pandemic (5–7).

Physical activity, sedentary time and sleep are also implicated as 24-hour movement behaviours are consistently associated with mental health outcomes (8–12). For example, a meta-analysis of 19 studies encompassing 11,826 participants aged 3–18 years found that increased moderate to vigorous physical activity (MVPA) and sleep, and decreased sedentary behaviour (SB), relative to other movement behaviours were associated with better social-emotional health (9).

To date, most studies investigating the associations between mental health and 24h movement behaviours have been cross-sectional. These studies have consistently demonstrated associations between SB and internalising problems relative to other activity behaviours. Further, reallocating time from SB to sleep or MVPA was associated with improved mental health outcomes (9). Longitudinal studies that examine changes in 24h movement behaviour composition over time, and their relationships with shifts in depressive symptoms among adolescents support these conclusions (9, 13). Activity intensity may be important, a recent meta-analysis of isotemporal substitution studies yielded mixed findings regarding influence of light physical activity (LPA) on mental health. One analysis indicated that replacing SB with MVPA or sleep but not LPA reduced the odds of depression, suggesting that at least moderate intensity physical activity is required to improve mental health outcomes (14). On the other hand, another meta-analysis found a reduced risk of depression when SB was replaced by LPA, suggesting that lower intensity activities may also offer benefits (15). Clearly further research is needed to elucidate the intensity, as well as types and contexts of physical activity that are most effective at improving children's mental health at a population level.

Focusing on intensity alone may obscure important differences in how and why individuals engage in sedentary or active behaviours and restrict interpretation and precision of intervention recommendations (16). For example, SB encompasses various postures such as sitting or lying down that could show distinct associations with health behaviours. Thigh-worn accelerometry, alongside advancements in processing algorithms, helps distinguish between postures and fine-grained activities separating sitting,

lying, standing, walking, walking, running, stair climbing, and cycling (17). This approach has resulted in 5 and 6 part compositions that have associations with cardiometabolic risk (18) and blood pressure (19). Given the significant increase in mental health problems, this more nuanced approach has not yet been applied to paediatric populations, missing a more granular analysis of the associations between behaviour and mental health indicators over a 24h period.

The device-based assessment of 24h movement in the MoMo 2.0-Study provided a unique opportunity to address these limitations. As a result, this study has two complementary and sequential aims. The first is to examine associations between a 4-part 24-hour physical behaviour composition [sleep, SB, LPA, MVPA] and internalising and externalising problems of children and adolescents and second to repeat the analysis using a more granular 11-component 24h “behaviour” composition [sleep, lie, sit, stand, move, slow walking, fast walking, run, stair, cycle, other]. In tandem, this will allow deeper insight into the relationships between movement behaviours within intensity categories and between intensities and mental health of children and adolescents.

Methods

Study design

The MoMo 2.0-Study investigated physical activity, physical fitness, health, and its determinants in a nationally representative cohort of children and adolescents aged 4–17 years in Germany. The assessment at the study centres consisted of anthropometric measurements, motor performance tests, a physical activity questionnaire, a health interview, and the option to wear an accelerometer. Data collection took place in 195 test centres between September 2023 and December 2024. Comprehensive details regarding the sampling strategy, testing protocols, and related procedures are described elsewhere (20).

Participants and settings

During the MoMo 2.0-Study, 3,995 children that completed the assessment at a study centre were invited to participate in an accelerometer sub-study. Exclusion criteria for participation included allergies to plasters, tape, or low-density polyethylene, skin conditions, scheduled MRIs or security checks involving metal detectors (e.g., at airports), or lack of informed consent. Of the 2,642 eligible children and adolescents, 2,542 (96.2%) returned the device. After quality checks and the application of valid week criteria, 1,584 participants aged 4–17 years (758 boys, 47.9%, and 825 girls, 52.1%) remained in the sample, representing 60.0% of the initial sample of 2,642 participants. On average, participants contributed 6.5 valid 24h periods of data for analysis.

Instruments and Procedures

Accelerometry

The study used the ActivPAL4.0 accelerometer (PALTechnologies Ltd., Glasgow, Scotland). The devices were initialised to record eight full days and seven nights of data collection. The day of distribution was treated as an adaptation phase and excluded from the analysis. The sensor was positioned on the front of the right thigh, 10 cm above the kneecap, with the leg bent at a 90° angle. Participants were provided with standardized instructions, which included detailed explanations of the accelerometer and data collection process. They were instructed to wear the device for eight consecutive days and to remove it only in unplanned or occurring cases of MRI, security checks, or skin irritation. If the device was removed, participants were asked to return it to the study coordinator using a prepaid, pre-addressed envelope.

Data Download and Data Processing

The data were downloaded using PALconnect (v9.1.0.148), and the raw data were exported as compressed, uncalibrated .csv files via PALbatch (v9.1.0.77). The recorded 24-hour physical behaviour data were processed using ActiPASS (Beta v2025.06.2) (21) for non-wear-time detection and physical behaviour classification (22–24). Accelerometry outcomes were calculated on two levels following the ActiPASS procedure. First, the physical behaviours of sleep, lying, sitting, standing, moving, slow walking, fast walking, cycling, stair walking, running, and “other” (i.e. all movements that could not be classified as another movement behaviour) are estimated. Then, a MET-value is attached to each physical behaviour and the physical behaviours are classified into broader categories: sleep, SB (lying, sitting), LPA (standing, moving, slow walking, other), and MVPA (fast walking, cycling, stair walking, running). To obtain age-specific results, the cadence thresholds for different activity intensities were customised within ActiPASS, following the heuristic thresholds recommended by Tudor-Locke et al. (25) for walking intensities. To ensure data validity, participants were required to have at least two weekdays and one weekend day with a minimum of 20 hours of recording per day to represent a valid week (26). See Fiedler et al. (27) for more detailed documentation.

Strengths and difficulties

Behavioural and emotional difficulties were evaluated using the German version of the Strengths and Difficulties Questionnaire (SDQ; (28)). Parents filled out the parent-report version of the SDQ alongside their children aged 4–10 years, while adolescents aged 11–17 years independently completed a self-report version. The four subscales (emotional symptoms, conduct problems, hyperactivity/inattention, peer relationship problems) used in this analysis contained five items each with responses rated on a 3-point Likert scale ("Not true," "Somewhat true," and "Certainly true," corresponding to 0, 1, and 2 points, respectively). Scores for internalising (emotional and peer relationship problems), and externalising problems (conduct and hyperactivity/inattention problems) were calculated by summing the points from the two respective subscales, resulting in two scores with a range of 0–20 points (28).

Co-variates

Age and sex were assessed via questionnaire.

Socioeconomic status (SES) was assessed as a part of the health interview with the parents and their children. An index was calculated based on education level and occupational status of the parents as well as the equivalised disposable household income. Education level and occupational status were assessed for both parents and each scored on a scale from 1 to 7 points. The higher scores between both parents were used or, in the case of a single parent household, education and occupational scores from the parent living with the child was used. Equivalised disposable household income was transformed into a score ranging from 1 to 7 points and then summed up with the education and occupation scores to form the SES score (range: 3–21). This score was then divided into quintiles based on the MoMo 2.0 sample. The lowest quintile (low SES) ranged from 3–11.7 compared to the highest quintile that ranged from 18.4–21 points (High SES). Participants within the middle three quintiles (11.8–18.3 points) were assigned a medium SES (29).

Body mass index (BMI) was calculated from measured height and weight without shoes and light clothing using a stadiometer (Seca 213) and a digital scale (Seca 813). BMI was first transformed into percentiles based on Kromeyer-Hauschild et al. (30) and then categorised into the categories severely underweight (< 3rd percentile), underweight (3rd to 10th percentile), normal weight (10th to 90th percentile), overweight (90th to 97th percentile), obese (> 97th percentile).

Statistical analysis

Compositional data analysis (CoDA) was employed to summarise daily time allocation across 24h movement behaviour and to assess their associations with internalising and externalising problems. Analyses were conducted separately for the child sample (age 4–10 years) and the adolescent sample (age 11–17 years) to account for different assessments of the SDQ and the associations between physical behaviours and mental health problems (31). Two compositions, a four-part composition consisting of sleep, SB, LPA, and MVPA and an eleven-part composition were used in two separate analyses. The 11-part composition comprised sleep, lying, sitting, standing, moving, slow walking, fast walking, cycling, stair walking, running, and other. The ‘other’ category was retained within the composition but excluded from the reported results due to its representation of brief, unclassifiable activity bouts. Zero values, for cycling (n = 40) and other behaviours (n = 68), were addressed using the log-ratio expectation-maximisation (lrEM) algorithm to preserve the ratios between behaviours without zeros (32). Zeros were replaced with values lower than the lowest observed value above zero using the lrEM-function from the zCompositions package (33). In both child and adolescent samples, compositional means were determined using the component-wise geometric mean, then standardised to prepositions of a total day (1440-minutes) for interpretability and to account for non-wear periods (4.58 ± 10.73 min/day).

Compositions were represented as isometric log-ratio (ilr) coordinates using sequential binary partitioning, enabling each 24h movement behaviour to be analysed relative to the others (34). The four-part and 11-part compositions resulted in three and 10 ilr coordinates, respectively, capturing the combined distribution of all parts of the composition.

Eight separate compositional linear regression models were constructed to evaluate the associations between 24h movement behaviour compositions, expressed as ilr coordinates, and internalising and externalising problems. All models were adjusted for age, sex, BMI, and SES. The overall effect of the composition on the dependent variables was assessed using type II ANOVA (34) via the 'car::Anova()' function, employing Wald Chi-squared tests according to the principle of marginality. Models exhibiting a significant main effect for the composition were subsequently explored with compositional isotemporal substitution to estimate changes in dependent variables resulting from reallocating time between 24h movement behaviour, with effects considered significant when the 95% confidence interval excluded zero. For the 11-part composition, time was only reallocated within each activity intensity group (SB: lying, sitting; LPA: standing, moving, slow walking; MVPA: fast walking, cycling, stair walking, running) and among the three walking behaviours (slow walking, fast walking, running). The reallocation range in plots reflects either 2 SD of the activity intensity group or behaviour with the smaller SD or the maximum reallocated time - whichever was smaller.

Results

From the 1,584 participants with valid accelerometry data, 41 participants were removed due to missing data in the SDQ internalising and externalising subscales, and a further 21 participants were removed due to missing BMI and/or SES data. Data from remaining 1,522 participants was therefore included in the analysis.

Descriptive results of the child and adolescent samples can be found in Table 1.

Table 1
Description of the child and adolescent samples

	Children (aged 4–10 years)			Adolescents (aged 11–17 years)		
	Boys	**Girls**	**Overall**	**Boys**	**Girls**	**Overall**
	N = 408	N = 441	N = 849	N = 323	N = 350	N = 673
Age years (sd)	8.0 (1.8)	8.0 (1.9)	8.0 (1.9)	13.9 (1.9)	14.2 (2.0)	14.0 (2.0)
Internalising problems	2.87 (2.68)	3.04 (2.68)	2.96 (2.68)	3.84 (2.70)	5.10 (3.35)	4.50 (3.12)
Externalising problems	5.74 (3.60)	4.84 (3.10)	5.27 (3.38)	5.59 (3.07)	4.73 (2.92)	5.14 (3.02)
Body-mass index						
Severely underweight	6 (1.5%)	9 (2.0%)	15 (1.8%)	12 (3.7%)	9 (2.6%)	21 (3.1%)
Underweight	21 (5.1%)	26 (5.9%)	47 (5.5%)	16 (5.0%)	30 (8.6%)	46 (6.8%)
Normal weight	348 (85%)	353 (80%)	701 (83%)	256 (79%)	265 (76%)	521 (77%)
Overweight	25 (6.1%)	37 (8.4%)	62 (7.3%)	29 (9.0%)	30 (8.6%)	59 (8.8%)
Obese	8 (2.0%)	16 (3.6%)	24 (2.8%)	10 (3.1%)	16 (4.6%)	26 (3.9%)
Socioeconomic status						
Low	55 (13%)	60 (14%)	115 (14%)	65 (20%)	68 (19%)	133 (20%)
Medium	255 (63%)	286 (65%)	541 (64%)	196 (61%)	202 (58%)	398 (59%)
High	98 (24%)	95 (22%)	193 (23%)	62 (19%)	80 (23%)	142 (21%)

Four-part composition

The compositional means for children and adolescents can be found in Table 2.

Table 2
Compositional means of the four-part compositions for children and adolescents (in min/day)

Sleep	**Children (aged 4–10 years)**	**Adolescents (aged 11–17 years)**
	558.66 (38.8%)	**502.31 (34.8%)**
Sedentary behaviour	558.49 (38.8%)	660.23 (45.8%)
Light physical activity	242.46 (16.8%)	208.05 (14.4%)
Moderate-to-vigorous physical activity	80.40 (5.6%)	69.41 (4.8%)

The ANOVAs revealed a significant ilr main effect ($F(3, 837) = 6.07$, $p < 0.001$, $\eta^2 = 0.021$) in the children's internalising problems model, but not in the children's externalising problems model $F(3, 837) = 0.53$, $p = 0.66$, $\eta^2 = 0.002$; see also supplement tables I & II). The results for the isotemporal substitution can be found in Fig. 1. The first panel of Fig. 1 (from Sleep to SB) can be used as an example for the interpretation of the results. This panel indicates that reallocating 60 minutes from sleep to SB (starting at x-axis 0 and moving to 60) is associated with a significantly (CIs don't cross the average problem score at x = 0) higher internalising problem score of around 0.5 points.

For the adolescent sample, the ANOVA from the internalising problems model shows a significant ilr main effect ($F(3, 661) = 3.59$, $p = 0.013$, $\eta^2 = 0.016$) but it is not significant in the externalising problems model ($F(3, 661) = 2.25$, $p = 0.081$, $\eta^2 = 0.010$; see also supplement tables III & IV). The results for the isotemporal substitution can be found in Fig. 2.

Eleven-part composition

The compositional means for children and adolescents can be found in Table 3. Of note, because activity behaviours were summarised to 24-hours using compositional methods, the estimated mean time in each behaviour depended on how the remaining behaviours were grouped; therefore, mean estimates may differ slightly between the 4-part and 11-part activity compositions.

Table 3
Compositional means of the eleven-part compositions for children and adolescents (in min/day)

Sleep	Children (aged 4–10 years)	Adolescents (aged 11–17 years)
	567.86 (39.4%)	**518.00 (36.0%)**
Lying	197.12 (13.7%)	228.98 (15.9%)
Sitting	357.77 (24.8%)	420.80 (29.3%)
Standing	108.56 (7.5%)	107.03 (7.4%)
Moving	91.83 (6.4%)	69.62 (4.9%)
Slow walking	38.33 (2.7%)	30.57 (2.2%)
Other	2.19 (0.2%)	0.46 (< 0.1%)
Fast walking	42.16 (2.9%)	48.22 (3.3%)
Cycling	6.83 (0.5%)	2.63 (0.2%)
Stair walking	14.22 (1.0%)	9.38 (0.7%)
Running	13.14 (0.9%)	4.31 (0.3%)

The ANOVAs revealed a significant ilr main effect ($F(10, 830) = 2.81$, $p = 0.002$, $\eta^2 = 0.033$) in the children's internalising problems model, but not in the children's externalising problems model $F(10, 830) = 1.63$, $p = 0.094$, $\eta^2 = 0.019$; see also supplement tables V & VI). The results for the isotemporal substitution within intensity categories can be found in Fig. 3 and between walking behaviours in supplement figure I.

For the adolescent sample, the ANOVAs from the internalising problems model ($F(10, 654) = 3.00$, $p = 0.001$, $\eta^2 = 0.044$) and the externalising problems model ($F(10, 654) = 3.12$, $p < 0.001$ $\eta^2 = 0.046$; see also supplement tables VII & VIII) show a significant ilr main effect. within intensity categories can be found in Figs. 4 and 5 for internalising and externalising problems respectively, and between walking behaviours in supplement figures II and III.

Discussion

This study examined associations between 24-hour movement behaviour composition and internalising and externalising problems in children and adolescents. We compared a conventional 4-part composition (sleep, sedentary behaviour, LPA, and MVPA) with a more granular 11-part behaviour labelled composition. The 11-part composition separated sedentary behaviour into lying and sitting, and physical activity into standing, moving, slow walking, fast walking, cycling, stair walking, running, and other activity. Internalising problems were associated with movement behaviour in both children and adolescents, in both compositions. Externalising problems were associated with 11-part composition

only for adolescents. Taken together, these findings suggest that the behavioural granularity of a 24-hour composition may not be a neutral methodological choice. Our data suggest that the choice of composition influences associations, particularly for externalising symptoms.

The findings on internalising problems are broadly in line with the CoDA literature. When considered relative to one another, physical activity, sedentary behaviour and sleep tend to be associated with internalising problems in young people. Moreover, the direction and magnitude of associations with individual behaviours appear to vary by age and behaviour type (9, 13).

In the 4-part model, the isotemporal substitution curves suggested that reallocating time from sedentary behaviour or LPA to MVPA was associated with lower internalising scores in children. Reallocating time away from sleep tended to be associated with higher internalising scores, regardless of which behaviour absorbed that time. In adolescents, reallocations from sedentary to light-activity showed the strongest associations, while sleep-related reallocations were comparatively weaker. This is broadly consistent with evidence that the time-use and relative contribution of specific movement behaviours to mental health may shift between childhood and adolescence (35). Furthermore, the context of the activity likely matters for internalising problems in adolescents as social aspects and enjoyment of the activity like playing games can be beneficial (36). Indeed, social participation and social skills can act as pathways between physical activity and mental health (37). Many types of LPA may not be structured physical activity but include activities such as walking to school or around town with friends, playing outside or moving around school which provide opportunities for social interaction an important to mental health in this age group (38).

The 11-part composition did not contradict outcomes from the 4-part but refined it. The mechanistic story commonly used is that internalising symptoms are closely tied to core physiological/regulatory processes like sleep-dependent emotion regulation, restorative arousal reduction from MVPA, and the general displacement of restorative behaviours by excess sedentary time (9, 39, 40). Because this pathway operates at the level of "which broad category are you in" (moving vs. sitting vs. sleeping), it survives collapsing sub-behaviours together and shows significant associations even when finer detail is aggregated into 4 parts. Adding more parts to the composition doesn't erase this signal, it just distributes it which is why both the 4-part and 11-part models reveal significant associations.

In both children and adolescents, the behaviours most strongly associated with internalising symptoms were concentrated at the highest end of the intensity spectrum. The association was not distributed evenly across all MVPA-type behaviours. Cycling fell within the same broad MVPA category as running in the 4-part composition, yet it showed a flat or even opposing association with internalising symptoms when compared to other MVPA behaviours. This divergence within a single 4-part category provides empirical support for the conceptual argument that broad categories such as “MVPA” can obscure heterogeneous, and possibly opposing, associations among their constituent sub-behaviours such as cycling and running (34, 41). Previous compositional work has similarly suggested that disaggregating physical activity may reveal associations with health outcomes that a standard four-behaviour

composition is too blunt to resolve (41). In our study, replacing 10 minutes of running by cycling or slow walking was associated with a clinically relevant deterioration of 1 internalising problem score in children. While this has to be interpreted with caution due to the small number of minutes of running in the sample, and the significant effect only emerging when running approaches 0 minutes, this may be an indicator for the benefit of higher intensity PA that is usually associated with intentional sports or exercise compared to everyday PA behaviour. The findings from this study suggest that the presence of an internalising association is relatively robust to behavioural aggregation. Importantly, the specific behaviour contributing most to that association appears to become visible only once physical activity is disaggregated by type.

In comparison, associations between 24-hour movement behaviour and externalising problems differed compared to internalising problems. For example, the 4-part standard composition was not significantly associated with externalising problems in children ($\eta^2 = 0.002$) or adolescents ($\eta^2 = 0.010$). In the 11-part composition, effect sizes increased in both age groups (children: $\eta^2 = 0.019$, $p = .094$; adolescents: $\eta^2 = 0.046$, $p < .001$) but only reached a significant association in adolescents. Because the more complex model faced a stricter statistical threshold, this pattern seems less likely to be explained solely by the addition of parameters. Instead, it suggests that the finer 11-part behavioural composition revealed effects that were previously hidden within a 4-part composition.

In our study, reallocating time from slow walking or moving to standing was associated with fewer externalising problems in adolescents. However, the cross-sectional design precludes causal inference, and this association may reflect reverse causation. For example, adolescents with greater restlessness, fidgeting or difficulty remaining stationary may accumulate more low-intensity ambulatory movement as manifestation of hyperactivity/inattention symptoms captured by the externalising problems scale. This interpretation is consistent with prospective cohort studies reporting that lower accelerometer-measured sedentary time in childhood predicted subsequent hyperactivity symptoms and ADHD diagnoses in early adolescence (42, 43).

Notably, the present work advances this narrative by demonstrating that the observed association is confined to a specific low-intensity behaviour, standing still, whereas other low-intensity activities such as moving or walking slowly showed no such association. In contrast, most other accelerometer-based studies rely on intensity categorization using cut point approaches where standing still is typically classified as SB. This highlights the benefit of using a more granular 11-part behavioural composition following recent developments to recognise activity types (44) as well as intensity categories (16). Furthermore, our findings extend this reasoning to generate key insight into the promotion of positive mental health in children and adolescents. Interventions or guidelines could for example recommend “increasing MVPA” to help prevent internalising symptoms in children. Our results indicate that recommendations can be more accurately defined into increasing vigorous, rhythmic, whole-body activities such as running, rather than just MVPA. Identifying and characterising the behaviour arguably yields the additional detail when promoting physical activity to this age group. “Do more MVPA” is not

easily understood while “run more” is a more actionable approach addressing the most effective behaviour directly (16).

Strengths and Limitations

To our knowledge, this is the first study to compare a conventional 4-part composition directly with a more granular 11-part composition within the same national sample. Because both compositions were applied to the same participants, the influence of behavioural resolution on detectable associations could be examined directly rather than inferred across separate studies.

The study also includes a number of limitations, first, all effect sizes were modest, including those that reached significance ($\eta^2 = 0.016$ to 0.046). This suggests that movement behaviour composition accounts for a small proportion of the variance in internalising and externalising symptoms. This is consistent with the broader view that movement behaviours are one of several contributors to youth mental health rather than a dominant determinant (9).

Second, several pivot coordinates in the 11-part adolescent model were estimated over narrow reallocation ranges and with wide confidence intervals, reflecting sparse behavioural data. This applied particularly to cycling, running and stair walking, each of which occupied less than 1% of the compositional day in adolescents yet is indicative of low levels of participation in these health promoting behaviours. This issue is further complicated by zero values and very short recorded durations. We imputed zero values for cycling; however, while accelerometers were fitted to the thigh, the short durations of running or cycling may reflect accelerometer misclassification rather than genuine engagement in these activities and may therefore be conceptually similar to zero values. In compositional analysis, it is important to distinguish rounded zeros, i.e. values below measurement resolution, from essential zeros, which represent true non-participation, because their treatment and interpretation differ (34). Accordingly, estimates of low-frequency behaviours should be interpreted with caution, as they may be more sensitive to non-participation effects or effects of very few highly active individuals.

Third, in line with recommended CoDA practice, pivot coordinates were interpreted only after a significant omnibus test of the overall composition (34). Consequently, isotemporal substitution results were not presented for the children’s externalising model.

Fourth, while this is a large nationwide study, the cross-sectional design does not permit causal inference. This is particularly relevant to the standing-to-movement externalising association, for which reverse causation is plausible.

Implications for research and future directions

These findings are consistent with a broader argument in the CoDA literature. With this in mind, the choice of behavioural granularity in a 24-hour composition may affect not only measurement precision but also whether an association can be detected at all (34, 41). For internalising symptoms in children,

guideline and intervention language framed around broad categories, such as MVPA and sedentary time, may risk diluting a more specific and potentially more actionable finding centred on vigorous, rhythmic activity such as running. For externalising symptoms in adolescents, standard activity-promotion messaging may not be well matched to the observed association. Specifically, spending more time standing still rather than moving or walking was associated with less externalising symptoms suggesting that these effects are rather a behavioural marker than a modifiable risk factor. This study provided novel insights into the relationship between 24h movement behaviours and externalising problems in adolescents by demonstrating that further differentiating low intensity activities into standing, moving and walking slowly can reveal meaningful information previously hidden in the broader intensity categories. Future studies could combine longitudinal designs and granular compositions with direct measures of sedentary behaviour content, such as screen-based versus non-screen sitting to advance the understanding between 24-h movement and externalising problems (13, 34). Additionally, future work might consider how sensor selection, wear location and analytical approaches, including machine-learning classification, could be designed to capture “restlessness related” movement patterns or those where participation is “outdoors” more directly and help to detect hyperactivity-related problems.

Future studies should critically evaluate the choice of reallocation range when applying compositional data analysis to 24-hour movement behaviours. Typically, compositional reallocation studies have examined sleep, SB, LPA, and MVPA, which contribute relatively large components of the 24-hour day. Fixed reallocations of 15–60 min/day are commonly reported, largely for convenience and interpretability (11). However, there remains no consensus on what constitutes a plausible reallocation range. To address this gap, we used a novel, data-informed approach, defining reallocations within a ± 2 SD range around mean compositions. Yet, this method faces limitations in fine-grained models: in our 11-part composition, several MVPA-related behaviours were brief and right-skewed, reaching the zero-minute boundary before the ± 2 SD threshold. Findings should therefore be interpreted cautiously, as the reallocation curves for behaviours nearing zero minutes tend to become strongly non-linear (J- or S-shaped) with wider confidence intervals (19), reflecting both sparse empirical support for extreme reallocations and qualitative differences between individuals who engage in these behaviours (e.g., running or cycling) and those who do not. These insights underscore the need for careful selection of reallocation strategies, consideration of behaviour-specific distributional properties, and transparent reporting of methodological decisions in future compositional analyses of 24-hour movement behaviours.

Conclusion

Behavioural granularity matters when examining associations between 24-hour physical behaviour and mental health in children and adolescents. Internalising symptoms were associated with movement behaviour composition regardless of granularity, with the specific contribution of running emerging in the 11-part model. Associations with externalising symptoms emerged only in the 11 part-model for adolescents where standing still was associated with fewer symptoms relative to other low intensity-

activities, suggesting certain activities may reflect symptoms rather than confer mental health benefits. Fine-grained analysis can reveal associations obscured by broader categories and may make findings easier to translate into activity specific, age-appropriate recommendations.

Abbreviations

BMI = body mass index

CoDA = compositional data analysis

ilr = isometric log-ratio

LPA = light physical activity

MVPA = moderate-to-vigorous physical activity

SB = sedentary behaviour

SES = socioeconomic status

SDQ = strengths and difficulties questionnaire

Declarations

Ethics approval and consent to participate

All procedures adhered to the ethical standards set by the Institutional Research Committee and complied with the Declaration of Helsinki (1975) and its subsequent amendments or equivalent ethical guidelines. Ethical approval for the MoMo 2.0-Study was granted by the Ethics Committee of the Karlsruhe Institute of Technology on November 6, 2023 (application number A2023-077). Informed consent was provided by legal guardians or participants (for those over 15 years).

Consent for publication

Not applicable.

Availability of data and materials

The dataset is subject to access restrictions to ensure data protection and compliance with ethical standards. Access can be granted upon a justified request and after signing a data use agreement. Requests should be addressed to the principal investigator of the MoMo 2.0-Study. Each request will be reviewed individually to ensure that the proposed use is consistent with the study's objectives and ethical guidelines.

Statistical analyses were performed using R and RStudio (R Core Team, 2025; RStudio Team, 2025). The code used to generate the study results is available upon reasonable request from the corresponding author. Please note that access may be subject to institutional or data-sharing agreements.

Competing interests

The authors declare that they have no competing interests

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Authors' contributions

Conceptualization: JF, LK, GS, NS; Methodology: JF, LK, NS; Data curation and formal analysis: JF, LK; Investigation: LK; Writing - original draft preparation: JF, LK; Writing - review and editing: JF, LK, GS, AW, NS; Funding acquisition: AW

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Figures

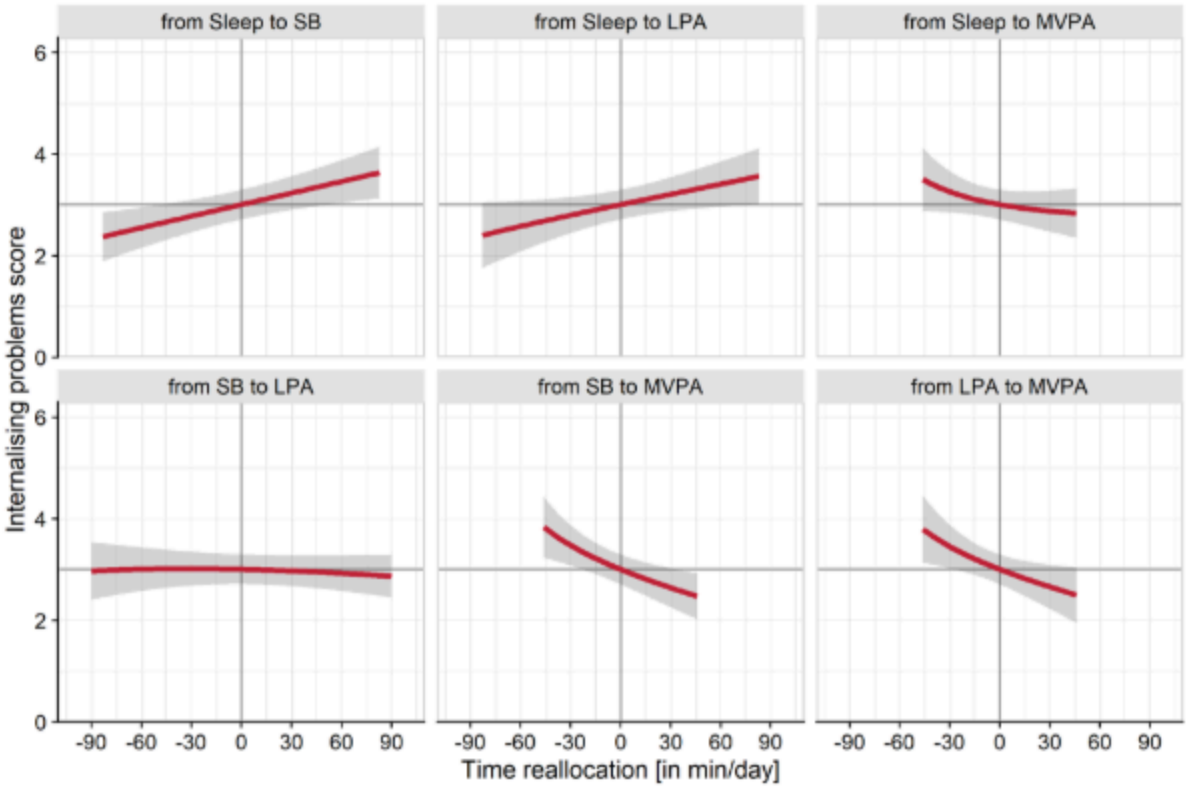

Figure 1

Reallocation between Sleep, SB, LPA and MVPA and its estimated changes in internalising problems in children

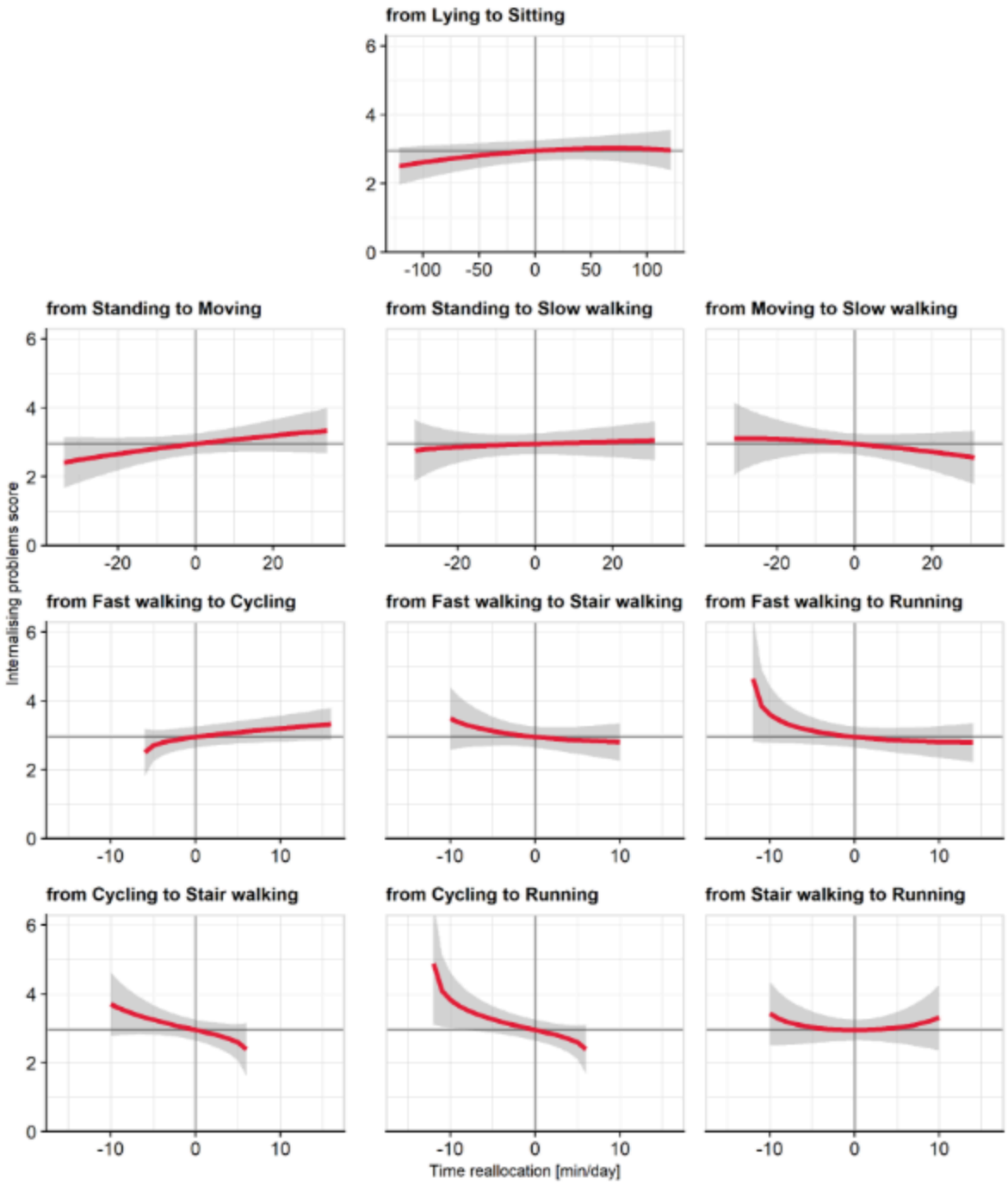

Figure 2

Reallocation between Sleep, SB, LPA and MVPA and its estimated changes in internalising problems in adolescents

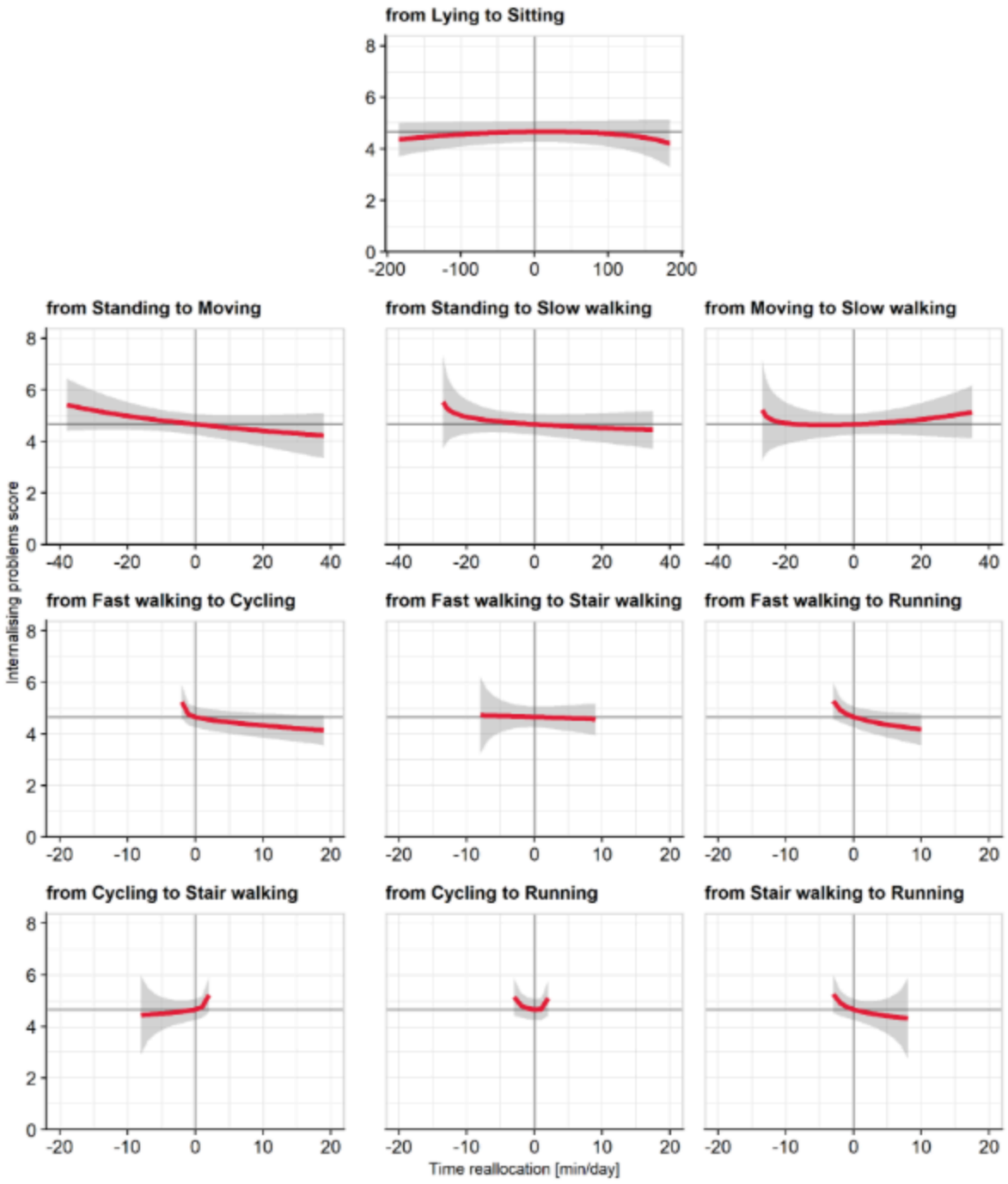

Figure 3

Reallocation between physical behaviours within intensity categories and its estimated changes in internalising problems in children (1st row: SB reallocations, 2nd row: LPA reallocations, 3rd and 4th row: MVPA reallocations)

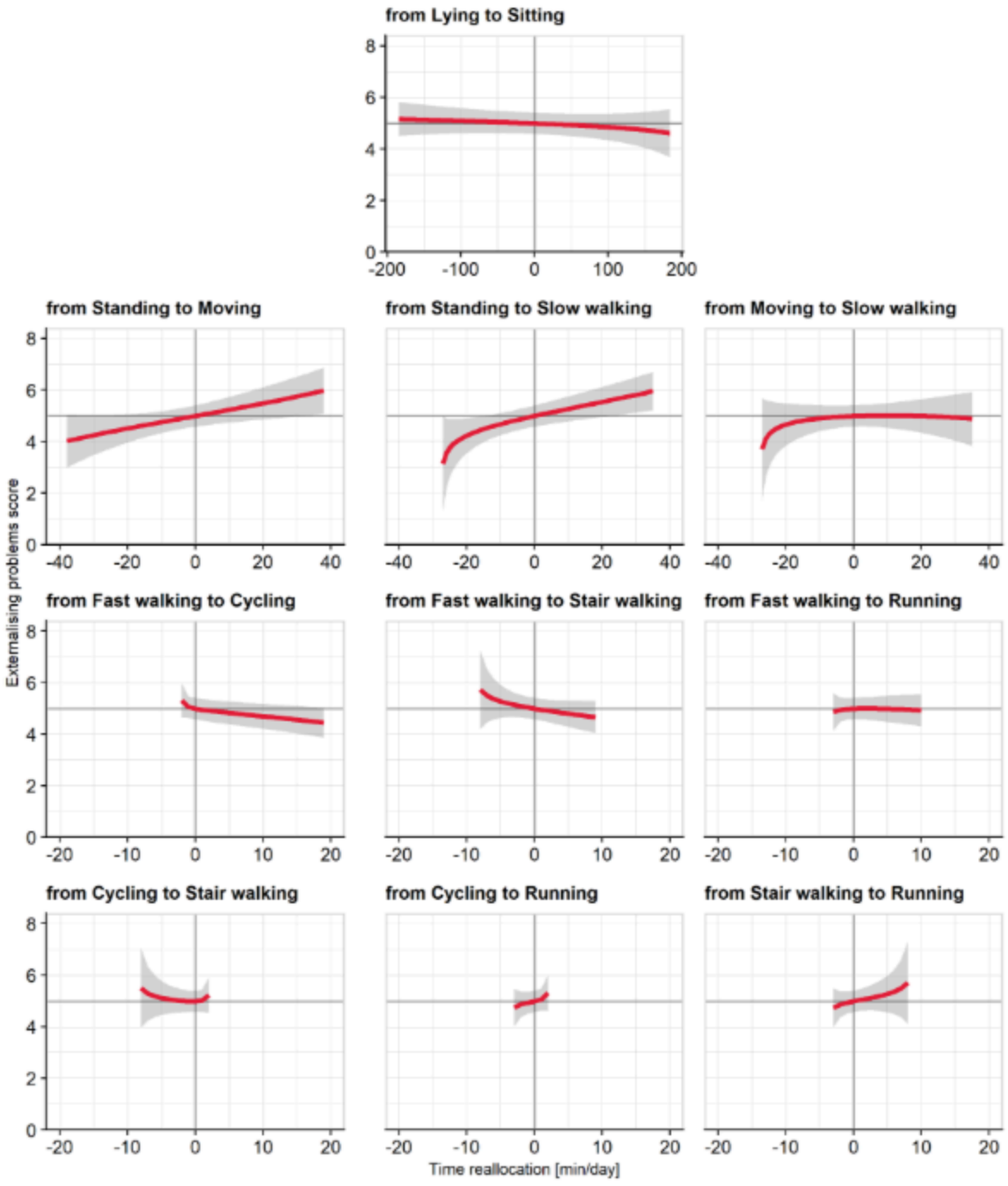

Figure 4

Reallocation between physical behaviours within intensity categories and its estimated changes in internalising problems in adolescents (1st row: SB reallocations, 2nd row: LPA reallocations, 3rd and 4th row: MVPA reallocations)

Supplementary Files

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