

The Association Between 24-Hour Movement Behaviors and Inhibitory Control in Preschool Children

Authors: Xu Qinyu, Mao Junqian, Chen Yuanyuan, Wen Xiaoni, Zhu Zhao-hong, Zhang Shichen, Zhang Shichen

Date: 2023-11-29T00:00:00+00:00

Abstract

Preschool children are in a “critical period” of inhibitory control development. Although previous studies have found that physical activity can improve children’s inhibitory control, how this ability is comprehensively affected by 24-hour movement behaviors remains controversial. Therefore, this study used relevant questionnaires to measure 24-hour movement behaviors, employed the Fish flanker and Emotional flanker paradigms to measure preschool children’s “cold” and “hot” inhibitory control, and utilized a compositional isotemporal substitution model to investigate the association between 24-hour movement behaviors and preschool children’s “cold” and “hot” inhibitory control. The results revealed that there was a significant association between preschool children’s 24-hour movement behaviors and their “cold” and “hot” inhibitory control. Moreover, increasing the time spent in moderate-to-vigorous physical activity at the expense of sedentary behavior or low-intensity physical activity, or increasing sleep duration at the expense of sedentary behavior or low-intensity physical activity, was associated with positive changes in preschool children’s “cold” and “hot” inhibitory control. This suggests that changes in “cold” and “hot” inhibitory control can be explained by the components of daily 24-hour movement behaviors in preschool children, and that these changes vary depending on different combinations of movement behaviors.

Full Text

Preamble

The Association Between 24-Hour Movement Behaviors and Inhibitory Control in Preschool Children: A Compositional Data Analysis Approach

Zhu Zhaohong², Zhang Shichen^{1*}, Xu Qinyu¹, Mao Junxi¹, Chen Yuanyuan¹,
Wen Xiaoni²

Abstract

Preschool children are in a critical period for the development of inhibitory control. While previous studies have found that physical activity can improve children's inhibitory control abilities, how this capacity is comprehensively influenced by 24-hour movement behaviors remains controversial. Therefore, this study employed relevant questionnaires to measure 24-hour movement behaviors, utilized the Fish Flanker and Emotional Flanker paradigms to assess preschool children's "cold" and "hot" inhibitory control, and adopted a compositional data isotemporal substitution model to explore the associations between 24-hour movement behaviors and both "cold" and "hot" inhibitory control in preschoolers. The results revealed significant associations between preschool children's 24-hour movement behaviors and their "cold" and "hot" inhibitory control. Specifically, increasing moderate-to-vigorous physical activity time at the expense of sedentary behavior or light physical activity, or increasing sleep duration at the expense of sedentary behavior or light physical activity, was associated with positive changes in preschool children's "cold" and "hot" inhibitory control. These findings suggest that changes in both "cold" and "hot" inhibitory control can be explained by the composition of daily 24-hour movement behaviors in preschool children, and that these changes vary depending on different combinations of movement behaviors.

Keywords: Preschool children, 24-hour movement behavior, "cold" and "hot" inhibitory control, compositional isotemporal substitution analysis

1. Introduction

Inhibitory control, a subcomponent of executive function, refers to the psychological process through which individuals control their attention, behavior, thoughts, or emotions to resist strong internal response tendencies or external temptations (Diamond & Adele, 2013). This ability plays a crucial role in the development of children's cognitive, emotional, and social functioning. Previous research in the field of child cognitive development has primarily focused on "cold" inhibitory control; however, Li Ying's (2011) research demonstrated that both "cold" and "hot" inhibitory control exert important influences on preschool children's development. "Cold" inhibitory control refers to preschool children's ability to self-regulate behavior and cognition in the absence of emotional arousal—for example, controlling impulses or selecting appropriate behavioral responses during tasks. In contrast, "hot" inhibitory control refers to preschool children's capacity to self-regulate behavior and emotions under emotionally evocative conditions (Wang Lingfeng, 2013). Research has shown that preschool children's emotional regulation abilities are equally critical for academic performance and higher cognitive functioning (Ghanbari et al., 2023;

Harrington et al., 2020). Moreover, in children's daily lives, "cold" and "hot" inhibitory control are typically intertwined, jointly shaping their behavior and decision-making.

Neuroimaging studies have indicated that children's prefrontal cortex (PFC) develops rapidly during the preschool period, particularly in the ventrolateral prefrontal cortex (VLPFC) and dorsolateral prefrontal cortex (DLPFC) regions closely associated with cognitive inhibition and emotional regulation (Garon et al., 2008). These regions are implicated in enhanced inhibitory control capabilities (Zelazo et al., 2008) and play pivotal roles in preschool children's inhibitory control development. Physical activity, sedentary behavior, and sleep are all movement behaviors closely related to preschool children's PFC development. Research has found that moderate physical activity can improve PFC function, a brain region intimately connected with inhibitory control (Hillman & Biggan, 2017). Through exercise, children may enhance neuroplasticity, promote PFC development, and thereby strengthen inhibitory control abilities (Ludyga et al., 2016). Meanwhile, sedentary behavior (particularly prolonged electronic device use) has been found to potentially lead to PFC hypoactivity, thereby affecting inhibitory control (Gapin & Etnier, 2010). Additionally, sleep deprivation is associated with decreased PFC function, while normal sleep helps maintain PFC stability and promotes inhibitory control, which may represent one of the key neural mechanisms underlying this capacity (Chaput et al., 2016).

Regarding behavioral manifestations of inhibitory control, physical activity, sedentary behavior, and sleep duration constitute three important factors influencing preschool children's inhibitory control. Extensive evidence demonstrates that physical activity is associated with inhibitory control abilities. For instance, aerobic exercise such as running can positively affect cognitive control, executive function, and academic achievement in children and adolescents (Best, 2010; Hillman et al., 2009; Koeppe et al., 2022; Park et al., 2023; Ziereis & Jansen, 2015). In contrast, excessive sedentary behavior is associated with lower cognitive levels and self-control abilities in children and adolescents (Carson et al., 2015; Li et al., 2022; McNeill et al., 2021; Rai et al., 2023). Simultaneously, adequate sleep duration also exerts positive effects on children's cognitive abilities and emotional management (Bernier et al., 2021; Bruni et al., 2020; Cho et al., 2017; Spencer, 2021). Although the aforementioned studies have confirmed that physical activity, sedentary behavior, and sleep can serve as independent predictors of inhibitory control, researchers have gradually reached consensus that these behaviors are interdependent and interactive, warranting simultaneous consideration. Since the total time spent on physical activity, sedentary behavior, and sleep within a day is fixed at 24 hours, these behaviors are termed "24-hour movement behaviors." Moreover, these behaviors are mutually exclusive—meaning that changing the time allocated to one behavior necessitates at least a compensatory change in another (Bezerra et al., 2021; Dumuid et al., 2019). Therefore, it is essential to analyze their comprehensive effects on individual health outcomes from the perspective of the overall combination of these three behaviors (Mekary, Michel et al., 2013; Mekary, Willett

et al., 2009; Prochaska, 2008).

In 2016, the Canadian Society for Exercise Physiology released the world's first integrated 24-hour movement guidelines for children and youth (5-17 years) (Tremblay et al., 2016), spearheading a new trend toward holistic research on 24-hour movement behaviors—namely physical activity (PA), sedentary behavior (SB), and sleep duration (SLP). The research evidence cited in these guidelines indicated that children's total physical activity volume was favorably related to physical, psychological/social, and cognitive health indicators (Poitras et al., 2016); longer durations of sedentary behaviors such as television viewing and screen time were associated with cardiometabolic disease risk scores, hostile/social behavior indicators, poorer physical fitness, and self-esteem (Carson et al., 2016); and shorter sleep duration in children was linked to poorer health status (Chaput et al., 2016). Subsequently, various countries released their own 24-hour movement guidelines, and current research in the 24-hour movement behavior domain has achieved considerable progress, with applications expanding from adults to older adult populations (Stamatakis et al., 2015). For example, studies have shown that reasonable 24-hour movement behavior patterns, such as adequate moderate-to-vigorous physical activity and reduced sedentary time, can yield positive health effects including decreased obesity rates and improved cardiovascular function (Chastin et al., 2015).

However, most current research has concentrated on adult populations, with studies targeting children, particularly preschool children, remaining relatively limited (Carson et al., 2017). Furthermore, existing research on 24-hour movement behaviors has primarily focused on body composition (Dumuid et al., 2018; Fairclough et al., 2017) and physical fitness (Carson et al., 2017; Ekblom-Bak et al., 2016), with few studies examining the relationship between 24-hour movement behaviors and advanced cognitive development in preschool children, particularly executive functions that are crucial for children's self-regulation (Zhang Ting et al., 2023; Carson et al., 2017; Grgic et al., 2018; Sampasa-Kanyinga et al., 2020). The preschool stage represents a critical period for children's physiological and psychological development, and cultivating healthy movement behavior patterns during this time can have profound long-term impacts on their health. Therefore, additional research is needed to investigate the comprehensive effects of 24-hour movement behavior patterns on cognitive development in preschool children.

Moreover, since 24-hour movement behaviors involve “compositional data”—where each component is non-negative and sums to a constant (24 hours)—they possess a “constant-sum constraint” characteristic (Chastin et al., 2015). Traditional regression analysis methods exhibit certain limitations when handling compositional data. Specifically, conventional regression typically assumes linear relationships between primary independent and dependent variables. Pedisic et al. (2017) and Dumuid et al. (2018) noted that in compositional data, components may exhibit non-linear relationships and multicollinearity, causing traditional regression models to inadequately capture these complex relationships

and potentially leading to model instability and reduced interpretability. Zhang Ting and Li Hongjuan's (2020) research identified compositional data analysis as the currently recognized methodological approach in relevant research, as it can estimate the comprehensive effects of the relative distribution of all 24-hour movement behaviors while resolving multicollinearity issues. The compositional isotemporal substitution model builds upon compositional data analysis by employing multivariate linear regression models based on log-ratio transformations to investigate the expected differences in dependent variables resulting from time reallocation among different movement behaviors.

Based on these considerations, this study employed a cross-sectional research design, utilizing compositional data analysis and the compositional isotemporal substitution model to explore the relationships between 24-hour movement behaviors and preschool children's "cold" and "hot" inhibitory control. The study further aimed to construct an optimal dose-response relationship pattern of 24-hour movement behaviors for preschool children's "cold" and "hot" inhibitory control, while providing scientific evidence for cultivating preschool children's inhibitory control abilities and for updating and revising 24-hour movement guidelines for Chinese preschool children.

2. Methods

2.1 Participants

Using G*Power 3.1 software (Faul et al., 2007), this study set the power value ($1-\beta$) at 0.8, α at 0.05, and effect size d at 0.15, yielding a required minimum sample size of 45 participants. The study recruited 66 preschool children aged 3-6 years (32 boys, 34 girls; mean age 5.02 ± 0.62 years) from a kindergarten in Shaanxi Province. Prior to the study's commencement, informed consent was obtained from all children's parents or legal guardians.

2.2 Measures

(1) 24-Hour Movement Behavior Questionnaire

The 24-hour movement behaviors included physical activity, sedentary behavior, and sleep duration. Physical activity and sedentary behavior were measured using the Preschool Children's Physical Activity Characteristics and Influencing Factors Questionnaire developed by Wu Haijun (2018), which demonstrates good reliability and validity. The physical activity questionnaire comprised 20 daily physical activity items (running, walking, sliding, etc.), assessing frequency and duration (minutes) of participation in the past week. Based on the ranges specified by the author, light physical activity (LPA) and moderate-to-vigorous physical activity (MVPA) were calculated. The sedentary behavior questionnaire included 8 daily sedentary items (video games, television watching, handicrafts, etc.), assessing frequency and duration (minutes) in the past week, from which sedentary behavior (SB) time was calculated.

Sleep duration (SLP) was assessed using the Nighttime Sleep Duration on Weekdays Questionnaire developed by domestic scholar Wu et al. (2017). The survey consisted of three questions: 1) “In the past month, what time does your child usually go to bed on weekdays? On weekends?” 2) “In the past month, what time does your child usually wake up on weekdays? On weekends?” 3) “Recall your child’s nap frequency and duration on weekdays/weekends in the past month, then check the total daytime sleep duration.” The specific calculation formula was: Sleep duration = [(weekday daytime sleep + weekday nighttime sleep) \times 5 + (weekend daytime sleep + weekend nighttime sleep) \times 2] / 7.

(2) “Cold” Inhibitory Control Task

The “cold” inhibitory control was measured using the Fish Flanker task programmed in Psychopy 2021.2.3. Experimental materials were presented as cartoon fish images, with the fish’s head orientation substituting for arrow directions in the classic task. All images were standardized in size and pixels, as shown in Figure 1 [Figure 1: see original paper]. The program presented stimuli in a horizontal array of five fish with different orientations, divided into congruent conditions (all fish facing the same direction) or incongruent conditions (multiple orientations present). Children’s task was to correctly identify the direction of the middle fish (target).

(3) “Hot” Inhibitory Control Task

The “hot” inhibitory control was measured using the Emotion Flanker task programmed in Psychopy 2021.2.3. Experimental materials were presented as cartoon happy and sad facial expression images, standardized in size and pixels, as shown in Figure 2 [Figure 2: see original paper]. The program presented stimuli in a horizontal array of five expressions with different valences, divided into congruent conditions (all expressions sharing the same valence: all positive/negative) or incongruent conditions (multiple valences present). Children’s task was to correctly identify the valence of the middle expression (target expression).

2.3 Procedure

This study employed individual administration. After participating preschool children’s guardians completed demographic questionnaires and relevant scales, children completed the Fish Flanker and Emotion Flanker tasks according to the following procedure:

- (1) Guardians completed demographic information questionnaires and relevant scales.
- (2) Under the experimenter’s guidance, children independently completed the Fish Flanker task. First, a black fixation cross “+” appeared at the center of the computer screen for 300ms, cueing the imminent start of the experiment. Subsequently, five horizontally arranged cartoon fish patterns were

presented at the screen center, with the middle fish serving as the target stimulus appearing at the fixation location for 3000ms.

The experiment was presented to children in a game-like format, telling them that a hungry fish was surrounded by other fish. This fish always appeared in the middle and would be happy if fed. Participants were required to respond via keypress when the image appeared, after which the program advanced to the next trial. If no response was made, the next fixation and stimulus automatically appeared after 3000ms. Participants' task was to respond to the middle fish's orientation while ignoring interference from surrounding fish. The hand assignment for left/right responses to fish direction was counterbalanced across children. The experiment consisted of practice (20 trials, requiring \$80% accuracy to proceed) and formal testing (40 randomly presented trials). This task examined correct responses in incongruent conditions; therefore, accuracy in incongruent conditions was recorded, with higher accuracy indicating better "cold" inhibitory control. The entire experiment was conducted in a quiet, well-lit room. The experimental procedure is shown in Figure 3 [Figure 3: see original paper].

- (3) After a 5-10 minute rest, children independently completed the Emotion Flanker task under the experimenter's guidance. First, a black fixation cross "+" appeared for 300ms, followed by five horizontally arranged cartoon expression patterns at screen center, with the middle expression as the target stimulus presented at the fixation location for 3000ms. Children were required to respond via keypress when the image appeared. The task was to respond to the middle expression's valence while ignoring surrounding expressions. If the middle expression was positive, participants responded with one hand (e.g., left hand) pressing the "F" key; if negative, they responded with the other hand (e.g., right hand) pressing the "H" key. Hand assignment for positive/negative expressions was counterbalanced across children. The experiment comprised practice (20 trials, \$80% accuracy required) and formal testing (40 randomly presented trials). This task examined correct responses in incongruent conditions; accuracy in incongruent conditions was recorded, with higher accuracy indicating better "hot" inhibitory control. The entire experiment was conducted in a quiet, well-lit room. The experimental procedure is shown in Figure 4 [Figure 4: see original paper].

2.4 Statistical Analysis

Statistical analyses followed the 24-hour movement behavior compositional analysis guidelines proposed by Chastin et al. (2015) and were conducted using R 4.0.5 software with the compositions package (Van den Boogaart & Tolosana-Delgado, 2008), robcompositions package (Templ et al., 2011), and lmtest package for compositional data analysis.

First, descriptive statistical methods for compositional data were employed to

present the central tendency and dispersion of 24-hour movement behavior data. Compositional geometric means were used to describe the central tendency of time data, while variation matrices—the log-variance of pairwise ratios between all components—were used to reflect data dispersion (Chastin et al., 2015). Smaller variance values indicated higher interdependence between two movement behaviors and greater likelihood of mutual conversion; larger variance values indicated lower interdependence.

Second, since traditional multiple linear regression methods often ignore the constant-sum constraint of compositional data, potentially creating spurious correlations and multicollinearity (Dumuid et al., 2018), this study performed multiple regression analysis based on isometric log-ratio (ILR) transformation of compositional data while controlling for confounding factors such as sex and age to examine associations between SLP, SB, LPA, MVPA and inhibitory control.

Finally, based on the fitted compositional regression model, time reallocation methods from previous studies were employed for isotemporal substitution analysis (Curtis et al., 2020; Dumuid, Pedisic et al., 2019; Dumuid, Stanford, Martin-Fernandez et al., 2018; Dumuid, Stanford, Pedisic et al., 2018). King's (2016) research found that 10 minutes/day represents both the minimal unit of physical activity accumulation for health benefits and the shortest duration of sedentary behavior that poses health risks. Therefore, this study used 10-minute units in substitution analyses, reallocating 10 minutes from one behavior to another while keeping total time (1440 minutes) and other activity times constant, calculating differences in inhibitory control between the reallocated time distribution and the original mean distribution. To more clearly present predicted changes in preschool children's inhibitory control across different reallocation durations, this study examined dose-response relationships by incrementing in 10-minute units up to 60 minutes for substitution pathways showing significant effects.

3. Results

3.1 Descriptive Statistics of 24-Hour Movement Behaviors

Compositional geometric means revealed that the average daily proportions of SB, LPA, MVPA, and SLP among preschool children in this study were 33.5%, 14.6%, 5.9%, and 46.0%, respectively. When converted to minutes per day, these corresponded to 482.36, 209.64, 85.60, and 662.40 min/d, respectively. Values approaching zero in the compositional variation matrix indicate that time spent in two behaviors is highly interdependent and most likely to be mutually converted. As shown in Table 1, the log-ratio variances between sleep and sedentary behavior, sleep and light physical activity, and sedentary behavior and light physical activity were all relatively small, indicating that time spent in sleep and sedentary behavior, sleep and light physical activity, and sedentary behavior and light physical activity were most likely to be interchanged among preschool children.

A ternary plot was used to visualize the distribution of time proportions across

24-hour movement behaviors in preschool children (Figure 5 [Figure 5: see original paper]). The results showed that the density curves in the MVPA time proportion direction were more dispersed compared to other movement behavior directions, indicating greater variability in MVPA time proportions among preschool children.

3.2 Associations Between 24-Hour Movement Behaviors and Inhibitory Control in Preschool Children

Multiple linear regression analysis based on isometric log-ratio transformation of compositional data was conducted to examine correlations between different 24-hour movement behaviors and “cold” and “hot” inhibitory control indices. As shown in Table 2, the relative distribution of 24-hour movement behavior time was significantly correlated with both “cold” and “hot” inhibitory control ($p < 0.001$). Specifically, sleep duration showed significant positive correlations with both “cold” ($\beta = 0.39$, $p = 0.006$) and “hot” ($\beta = 0.63$, $p < 0.001$) inhibitory control. Moderate-to-vigorous physical activity was significantly positively correlated with both “cold” ($\beta = 0.11$, $p < 0.001$) and “hot” ($\beta = 0.08$, $p = 0.017$) inhibitory control. Light physical activity showed a significant negative correlation with “hot” inhibitory control ($\beta = -0.20$, $p = 0.018$).

3.3 Isotemporal Substitution Analysis of 24-Hour Movement Behaviors and Inhibitory Control

Table 3 displays the predicted differences in “cold” and “hot” inhibitory control when 10 minutes are reallocated from the behavior in the column to the behavior in the row while keeping other behaviors constant.

For “cold” inhibitory control, reallocating 10 minutes from SLP to SB or LPA decreased predicted “cold” inhibitory control by 0.01 (SB: $\beta = -0.010$, 95% CI [-0.017, -0.004]) or 0.012 (LPA: $\beta = -0.012$, 95% CI [-0.018, -0.005]) units compared to the predicted mean. Reallocating 10 minutes from SB to SLP or MVPA increased predicted “cold” inhibitory control by 0.01 (SLP: $\beta = 0.010$, 95% CI [0.004, 0.017]) or 0.011 (MVPA: $\beta = 0.011$, 95% CI [0.005, 0.017]) units. Reallocating 10 minutes from LPA to SLP or MVPA increased predicted “cold” inhibitory control by 0.012 (SLP: $\beta = 0.012$, 95% CI [0.005, 0.019]) or 0.013 (MVPA: $\beta = 0.013$, 95% CI [0.005, 0.021]) units. Reallocating 10 minutes from MVPA to SB or LPA decreased predicted “cold” inhibitory control by 0.012 (SB: $\beta = -0.012$, 95% CI [-0.018, -0.005]) or 0.013 (LPA: $\beta = -0.013$, 95% CI [-0.021, -0.005]) units.

For “hot” inhibitory control, reallocating 10 minutes from SLP to SB or LPA decreased predicted “hot” inhibitory control by 0.01 (SB: $\beta = -0.010$, 95% CI [-0.017, -0.004]) or 0.017 (LPA: $\beta = -0.017$, 95% CI [-0.024, -0.010]) units. Reallocating 10 minutes from SB to SLP increased predicted “hot” inhibitory control by 0.01 ($\beta = 0.010$, 95% CI [0.003, 0.017]) units. Reallocating 10 minutes from LPA to SLP or MVPA increased predicted “hot” inhibitory control by

0.017 (SLP: $\beta=0.017$, 95% CI [0.010, 0.025]) or 0.014 (MVPA: $\beta=0.014$, 95% CI [0.005, 0.022]) units. Reallocating 10 minutes from MVPA to LPA decreased predicted “hot” inhibitory control by 0.013 ($\beta=-0.013$, 95% CI [-0.022, -0.004]) units.

3.4 Dose-Response Relationship Between 24-Hour Movement Behavior Reallocation and Inhibitory Control

To explore patterns of inhibitory control ability changes during sustained time reallocation, this study examined dose-response relationships between different reallocation durations and both “cold” and “hot” inhibitory control in preschool children by incrementing in 10-minute units up to 60 minutes for compositional elements showing significant substitution effects.

As shown in Figures 6 [Figure 6: see original paper] and 7 [Figure 7: see original paper], this study found that the reallocation effects between MVPA and other movement behaviors (LPA, SB) were asymmetrical—that is, the enhancing effect on “cold” inhibitory control when MVPA time substituted for other behaviors was smaller than the decreasing effect when other behaviors substituted for MVPA. In contrast, the mutual substitution between LPA and SLP showed relatively symmetrical effects on both “cold” and “hot” inhibitory control. For instance, substituting 10 minutes of LPA for SLP decreased “cold” inhibitory control by 0.012 units, while the reverse substitution increased it by 0.012 units; “hot” inhibitory control decreased by 0.017 units and increased by 0.017 units, respectively (see Table 4).

Second, dose-response curves revealed that as MVPA time continued to substitute for LPA and SB, preschool children’s “cold” inhibitory control levels continuously improved, with the greatest improvement occurring when MVPA substituted for LPA, indicating the largest effect size. For “hot” inhibitory control, sleep duration substituting for LPA produced the greatest enhancement, showing the largest effect size.

4. Discussion

This study aimed to investigate the relationship between 24-hour movement behaviors and inhibitory control in preschool children, as well as the isotemporal substitution effects between different movement behaviors. While previous research has examined relationships between preschool children’s physical activity and “cold” and “hot” inhibitory control (Giordano & Alesi, 2022; Li et al., 2011; Tsai, 2009), or between sedentary behavior (Chen & Muggleton, 2020; McNeill et al., 2021; Tandon et al., 2018), sleep (Bernier et al., 2021; Chen et al., 2021) and “cold” and “hot” inhibitory control, to the authors’ knowledge, this study represents the first comprehensive analysis of the relationship between preschool children’s 24-hour movement behaviors and both their “cold” and “hot” inhibitory control. Meanwhile, previous systematic reviews on physical activity, sedentary behavior, and sleep duration in relation to cognitive devel-

opment in preschool children (Carson, Hunter et al., 2016; Carson, Kuzik et al., 2015; Reynaud et al., 2018) have indicated that relevant research is scarce and the evidence grade for associations is “very low,” underscoring the necessity for additional studies. Moreover, although some studies (Bu et al., 2021; Curtis et al., 2020; Stamatakis et al., 2015) have explored isothermal substitution relationships between 24-hour movement behaviors and health outcomes in other age groups, this is the first investigation of the relationship between 24-hour movement behaviors and preschool children’s “cold” and “hot” inhibitory control within the framework of compositional data and isothermal substitution methodology.

The main findings of this study indicate that when different movement behaviors are considered as components of a 24-hour behavioral composition, a significant positive correlation emerges, with these behaviors collectively explaining 33% and 29% of variance in “cold” and “hot” inhibitory control, respectively. Furthermore, we found that reallocating individual components of the daily 24-hour movement behavior composition was associated with changes in both “cold” and “hot” inhibitory control. In a longitudinal study, Li Xin et al. (2022) evaluated the relationship between 12 weeks of after-school exercise and inhibitory control in adolescents, finding that the high-dose exercise group showed significantly better inhibitory control than the control group, while the low-dose exercise group showed no significant effects. Our results align with Li Xin et al.’s findings, suggesting that for inhibitory control, increasing MVPA while reducing SB or LPA may be expected to produce significant and positive outcomes. Indeed, from an ecological perspective, inhibitory control abilities may function during children’s play periods (Koeppe et al., 2022). Therefore, this study anticipated that MVPA would be related to inhibitory control, and that increasing MVPA and reducing SB in children’s lives might have long-term beneficial effects on their inhibitory control.

4.1 Association Between 24-Hour Movement Behaviors and “Cold” Inhibitory Control

In examining the association between “cold” inhibitory control and 24-hour movement behaviors, results showed that SLP and MVPA were significantly positively correlated with “cold” inhibitory control ($p < 0.05$), consistent with previous research (Cremone et al., 2017; Li et al., 2022). Isothermal substitution results revealed that reallocating 10 minutes of SB or LPA to MVPA produced significant improvements in preschool children’s “cold” inhibitory control, whereas reallocating 10 minutes of SB to LPA did not yield significant improvements. This finding reveals an important issue regarding physical activity in this age group: higher physical activity intensity is associated with better “cold” inhibitory control performance. This may be attributable to benefits from increased cerebral blood flow during moderate-to-vigorous physical activity (Khan & Hillman, 2014). Additionally, reallocating 10 minutes of SB or LPA to SLP also significantly improved preschool children’s “cold” inhibitory

control, highlighting the important role of sleep in the development of “cold” inhibitory control in preschool children.

However, this study’s results indicated that substituting 10 minutes of LPA for SB had no significant effect on “cold” inhibitory control. Therefore, at the physical activity level, only MVPA appears to exert meaningful effects on “cold” inhibitory control. This point is supported by a systematic review of preschool children (Poitras et al., 2016) showing that multiple health indicators, including physical fitness, were only associated with MVPA. Although substituting MVPA time for both LPA and SB could promote the development of preschool children’s “cold” inhibitory control, dose-response curves further indicated that MVPA substituting for LPA produced the optimal promoting effect on “cold” inhibitory control.

4.2 Association Between 24-Hour Movement Behaviors and “Hot” Inhibitory Control

Previous research linking physical activity domains to inhibitory control in preschool children has primarily focused on “cold” inhibitory control (Tandon et al., 2018). While improving “cold” inhibitory control throughout the lifespan is undoubtedly crucial, particularly in child populations where “cold” inhibitory control may be related to physical and mental health (Carson et al., 2016; Li et al., 2022), academic development (Jiang et al., 2022), and higher cognitive functions (Wang & Chen, 2012), recent studies have found that emotional inhibition ability—“hot” inhibitory control—also plays a vital role in preschool children’s cognitive development and behavioral problem prevention (Romero-López et al., 2021), yet is often overlooked in research.

In examining the association between “hot” inhibitory control and 24-hour movement behaviors, results showed that SLP, LPA, and MVPA were all significantly positively correlated with “hot” inhibitory control ($p < 0.05$). Isotemporal substitution results indicated that reallocating 10 minutes of SB or LPA to SLP significantly improved preschool children’s “hot” inhibitory control. Reallocating 10 minutes of LPA to MVPA also significantly improved “hot” inhibitory control. Furthermore, when reducing SLP and increasing SB or LPA, “hot” inhibitory control showed negative changes of 0.01 or 0.017 units at the 10-minute reallocation level, while reducing MVPA and increasing LPA produced a 0.013-unit change in “hot” inhibitory control at the 10-minute reallocation level. These findings indicate that MVPA and SLP play crucial roles in the development of “hot” inhibitory control in preschool children, consistent with previous research (Spencer, 2021; Yu et al., 2022).

The primary strength of this study lies in its novel approach to investigating relationships between different movement behaviors and inhibitory control. Moreover, to the authors’ knowledge, this is the first work to examine compositional data analysis and isotemporal substitution in the context of preschool children’s “cold” and “hot” inhibitory control. However, despite its novelty, this study has

several limitations. The compositional data analysis method used did not distinguish between types of activities within sedentary behavior. Indeed, evidence suggests that specific forms of sedentary behavior (e.g., reading, puzzles) may have positive effects on children's cognitive development (Lemos et al., 2021). Therefore, exploring relationships between different sedentary patterns and children's cognitive development could serve as a direction for future investigation. Additionally, this study employed a cross-sectional design; although significant correlations were identified between variables, causal relationships cannot be inferred. Furthermore, the current study only recruited preschool children from Shaanxi Province, and the results may not be generalizable to preschool children in other regions. Finally, this study used self-report questionnaires to collect data, which are susceptible to recall bias and social desirability effects.

This study demonstrates that changes in both “cold” and “hot” inhibitory control can be explained by the composition of daily 24-hour movement behaviors in preschool children. The current research indicates that when analyzed as a continuum, 24-hour movement behaviors significantly predict children's inhibitory control. The results confirm that increasing MVPA time at the expense of SB and LPA, or increasing SLP time at the expense of SB and LPA, is associated with positive changes in preschool children's “cold” and “hot” inhibitory control. Future educators aiming to enhance preschool children's “cold” and “hot” inhibitory control levels should focus on promoting the overall 24-hour movement behavior profile, with increasing MVPA and SLP while reducing SB and LPA representing effective approaches for improving preschool children's inhibitory control abilities.

References

- Bernier, A., Cimon-Paquet, C., & Tétréault, É. (2021). Sleep development in preschool predicts executive functioning in early elementary school. In *Advances in child development and behavior* (Vol. 60, pp. 159-178).
- Best, J. R. (2010). Effects of physical activity on children's executive function: Contributions of experimental research on aerobic exercise. *Developmental review*, 30(4), 331-351.
- Bezerra, T. A., Clark, C. C. T., Souza Filho, A. N. D., Fortes, L. D. S., Mota, J. A. P. S., Duncan, M. J., & Martins, C. M. D. L. (2021). 24-hour movement behaviour and executive function in preschoolers: a compositional and isotemporal reallocation analysis. *European journal of sport science*, 21(7), 1064-1072.
- Bruni, O., Melegari, M. G., Esposito, A., Sette, S., Angriman, M., Apicella, M., ... & Ferri, R. (2020). Executive functions in preschool children with chronic insomnia. *Journal of Clinical Sleep Medicine*, 16(2), 231-241.
- Bu, H., He, A., Gong, N., Huang, L., Liang, K., Kastelic, K., ... & Chi, X. (2021). Optimal movement behaviors: correlates and associations with anxiety symptoms among Chinese university students. *BMC public health*, 21,

- Carson, V., Chaput, J. P., Janssen, I., & Tremblay, M. S. (2017). Health associations with meeting new 24-hour movement guidelines for Canadian children and youth. *Preventive Medicine*, 95, 7-13.
- Carson, V., Hunter, S., Kuzik, N., Wiebe, S. A., Spence, J. C., Friedman, A., ... & Hinkley, T. (2016). Systematic review of physical activity and cognitive development in early childhood. *Journal of science and medicine in sport*, 19(7), 573-578.
- Carson, V., Hunter, S., Kuzik, N., Gray, C. E., Poitras, V. J., Chaput, J. P., Saunders, T. J., Katzmarzyk, P. T., Okely, A. D., Connor Gorber, S., Kho, M. E., Sampson, M., Lee, H., & Tremblay, M. S. (2016). Systematic review of sedentary behaviour and health indicators in school-aged children and youth: an update. *Applied physiology, nutrition, and metabolism = Physiologie appliquee, nutrition et metabolisme*, 41(6 Suppl 3), S240-S265.
- Carson, V., Kuzik, N., Hunter, S., Wiebe, S. A., Spence, J. C., Friedman, A., ... & Hinkley, T. (2015). Systematic review of sedentary behavior and cognitive development in early childhood. *Preventive medicine*, 78, 115-122.
- Carson, V., Lee, E. Y., Hewitt, L., Jennings, C., Hunter, S., Kuzik, N., Stearns, J. A., Unrau, S. P., Poitras, V. J., Gray, C., Adamo, K. B., Janssen, I., Okely, A. D., Spence, J. C., Timmons, B. W., Sampson, M., & Tremblay, M. S. (2017). Systematic review of the relationships between physical activity and health indicators in the early years (0-4 years). *BMC public health*, 17(Suppl 5), 854.
- Chaput, J. P., Gray, C. E., Poitras, V. J., Carson, V., Gruber, R., Olds, T., Weiss, S. K., Connor Gorber, S., Kho, M. E., Sampson, M., Belanger, K., Eryuzlu, S., Callender, L., & Tremblay, M. S. (2016). Systematic review of the relationships between sleep duration and health indicators in school-aged children and youth. *Applied physiology, nutrition, and metabolism = Physiologie appliquee, nutrition et metabolisme*, 41(6 Suppl 3), S266-S282.
- Chastin, S. F., Palarea-Albaladejo, J., Dontje, M. L., & Skelton, D. A. (2015). Combined effects of time spent in physical activity, sedentary behaviors and sleep on obesity and cardio-metabolic health markers: a novel compositional data analysis approach. *PLoS one*, 10(10), e0139984.
- Chen, C. Y., & Muggleton, N. G. (2020). Electrophysiological investigation of the effects of Tai Chi on inhibitory control in older individuals. *Progress in Brain Research*, 253, 229-242.
- Chen, Y., Wang, Y., Wang, S., Zhang, M., & Wu, N. (2021). Self-reported sleep and executive function in early primary school children. *Frontiers in Psychology*, 12, 793000.
- Cho, S., Philbrook, L. E., Davis, E. L., & Buss, K. A. (2017). Sleep duration and RSA suppression as predictors of internalizing and externalizing behaviors. *Developmental psychobiology*, 59(1), 60-69.

- Cremone, A., McDermott, J. M., & Spencer, R. M. (2017). Naps enhance executive attention in preschool-aged children. *Journal of Pediatric Psychology*, 42(8), 837-845.
- Curtis, R. G., Dumuid, D., Olds, T., Plotnikoff, R., Vandelanotte, C., Ryan, J., ... & Maher, C. (2020). The association between time-use behaviors and physical and mental well-being in adults: a compositional isotemporal substitution analysis. *Journal of Physical Activity and Health*, 17(2), 197-203.
- Diamond, A. (2013). Executive functions. *Annual review of psychology*, 64, 135-168.
- Dumuid, D., Pedišić, Ž., Stanford, T. E., Martín-Fernández, J. A., Hron, K., Maher, C. A., ... & Olds, T. (2019). The compositional isotemporal substitution model: a method for estimating changes in a health outcome for reallocation of time between sleep, physical activity and sedentary behaviour. *Statistical methods in medical research*, 28(3), 846-857.
- Dumuid, D., Stanford, T. E., Martín-Fernández, J. A., Pedišić, Ž., Maher, C. A., Lewis, L. K., ... & Olds, T. (2018). Compositional data analysis for physical activity, sedentary time and sleep research. *Statistical methods in medical research*, 27(12), 3726-3738.
- Dumuid, D., Stanford, T. E., Pedišić, Ž., Maher, C., Lewis, L. K., Martín-Fernández, J. A., ... & Olds, T. (2018). Adiposity and the isotemporal substitution of physical activity, sedentary time and sleep among school-aged children: a compositional data analysis approach. *BMC public health*, 18, 1-10.
- Eklom-Bak, E., Eklom, Ö., Bergström, G., & Börjesson, M. (2016). Isotemporal substitution of sedentary time by physical activity of different intensities and bout lengths, and its associations with metabolic risk. *European journal of preventive cardiology*, 23(9), 967-974.
- Fairclough, S. J., Dumuid, D., Taylor, S., Curry, W., McGrane, B., Stratton, G., ... & Olds, T. (2017). Fitness, fatness and the reallocation of time between children's daily movement behaviours: an analysis of compositional data. *International Journal of Behavioral Nutrition and Physical Activity*, 14(1), 1-12.
- Faul, F., Erdfelder, E., Lang, A. G., & Buchner, A. (2007). G* Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior research methods*, 39(2), 175-191.
- Gapin, J., & Etnier, J. L. (2010). The relationship between physical activity and executive function performance in children with attention-deficit hyperactivity disorder. *Journal of sport & exercise psychology*, 32(6), 753-763.
- Garon, N., Bryson, S. E., & Smith, I. M. (2008). Executive function in preschoolers: a review using an integrative framework. *Psychological bulletin*, 134(1), 31-60.
- Ghanbari, S., Vahidi, E., Behzadpoor, S., Goudarzi, Z., & Ghabezi, F. (2023).

Parental reflective functioning and preschool children's psychosocial functioning: the mediating role of children's emotion regulation. *European Journal of Developmental Psychology*, 20(2), 229-250.

Giordano, G., & Alesi, M. (2022). Does physical activity improve inhibition in kindergarteners? A pilot study. *Perceptual and Motor Skills*, 129(4), 1001-1013.

Grgic, J., Dumuid, D., Bengoechea, E. G., Shrestha, N., Bauman, A., Olds, T., & Pedisic, Z. (2018). Health outcomes associated with reallocations of time between sleep, sedentary behaviour, and physical activity: a systematic scoping review of isotemporal substitution studies. *International Journal of Behavioral Nutrition and Physical Activity*, 15(1), 1-68.

Harrington, E. M., Trevino, S. D., Lopez, S., & Giuliani, N. R.. (2020). Emotion regulation in early childhood: implications for socioemotional and academic components of school readiness. *Emotion*, 20(1), 48-53.

Hillman, C. H., & Biggan, J. R. (2017). A Review of Childhood Physical Activity, Brain, and Cognition: Perspectives on the Future. *Pediatric exercise science*, 29(2), 170-176.

Hillman, C. H., Pontifex, M. B., Raine, L. B., Castelli, D. M., Hall, E. E., & Kramer, A. F. (2009). The effect of acute treadmill walking cognitive control academic achievement preadolescent children. *Neuroscience*, 159(3), 1044-1054.

Jiang, S., Ma, L., & Chen, B. (2023). Dynamic engagement of cognitive control in intra-sentential code-switching during comprehension. *Bilingualism: Language and Cognition*, 26(1), 62-77.

Khan, N. A., & Hillman, C. H. (2014). The relation of childhood physical activity and aerobic fitness to brain function and cognition: a review. *Pediatric exercise science*, 26(2), 138-146.

King, W. C., Chen, J. Y., Courcoulas, A. P., Mitchell, J. E., Wolfe, B. M., Patterson, E. J., ... & Belle, S. H. (2016). Objectively-measured sedentary time and cardiometabolic health in adults with severe obesity. *Preventive medicine*, 84, 12-18.

Koepp, A. E., Gershoff, E. T., Castelli, D. M., & Bryan, A. E. (2022). Preschoolers' executive functions following indoor and outdoor free play. *Trends in Neuroscience and Education*, 100182.

Lemos, L., Clark, C., Brand, C., Pessoa, M. L., Gaya, A., Mota, J., ... & Martins, C. (2021). 24-hour movement behaviors and fitness in preschoolers: A compositional and isotemporal reallocation analysis. *Scandinavian Journal of Medicine & Science in Sports*, 31(6), 1371-1379.

Li, L., Yu, Q., Zhao, W., Herold, F., Cheval, B., Kong, Z., ... & Zou, L. (2021). Physical activity and inhibitory control: The mediating role of sleep quality and sleep efficiency. *Brain Sciences*, 11(5), 664.

- Li, S., Guo, J., Zheng, K., Shi, M., & Huang, T. (2022). Is sedentary behavior associated with executive function in children and adolescents? A systematic review. *Frontiers in Public Health*, 10, 832845.
- Li, X., Wang, Z., Wang, Y., Li, X., & Li, D. (2022). Effect of exercise on inhibitory control is dose-dependent for adolescents. *Sports Medicine and Health Science*, 4(1), 54-60.
- Li, Y. (2011). *The development of preschool children's inhibition control, its influencing factors and its relationship with social adaptation* (Unpublished master's thesis). Shanghai Normal University. [李滢. (2011). 学龄前儿童抑制控制的发展、影响因素及其与社会适应的关系 (硕士学位论文). 上海师范大学.]
- Li, Y., Zhou, T., Lu, Y., Sang, M., Liu, J., He, X., & Quan, M. (2022). The association between the health-related physical fitness and inhibitory control in preschool children. *BMC pediatrics*, 22(1), 1-10.
- Ludyga, S., Gerber, M., Brand, S., Holsboer-Trachsler, E., & Pühse, U. (2016). Acute effects of moderate aerobic exercise on specific aspects of executive function in different age and fitness groups: A meta-analysis. *Psychophysiology*, 53(11), 1611-1626.
- McNeill, J., Howard, S. J., Vella, S. A., & Cliff, D. P. (2021). Cross-sectional associations of application use and media program viewing with cognitive and psychosocial development in preschoolers. *International journal of environmental research and public health*, 18(4), 1608.
- Mekary, R. A., Lucas, M., Pan, A., Okereke, O. I., Willett, W. C., Hu, F. B., & Ding, E. L. (2013). Isotemporal substitution analysis for physical activity, television watching, and risk of depression. *American journal of epidemiology*, 178(3), 474-483.
- Mekary, R. A., Willett, W. C., Hu, F. B., & Ding, E. L. (2009). Isotemporal substitution paradigm for physical activity epidemiology and weight change. *American journal of epidemiology*, 170(4), 519-527.
- Park, S., Chun, H., Etnier, J. L., & Yun, D. (2023). Exploring the Mediating Role of Executive Function in the Relationship between Aerobic Fitness and Academic Achievement in Adolescents. *Brain Sciences*, 13(4), 614.
- Pedišić, Ž., Dumuid, D., & S Olds, T. (2017). Integrating sleep, sedentary behaviour, and physical activity research in the emerging field of time-use epidemiology: definitions, concepts, statistical methods, theoretical framework, and future directions. *Kinesiology*, 49(2.), 252-269.
- Poitras, V. J., Gray, C. E., Borghese, M. M., Carson, V., Chaput, J. P., Janssen, I., ... & Tremblay, M. S. (2016). Systematic review of the relationships between objectively measured physical activity and health indicators in school-aged children and youth. *Applied physiology, nutrition, and metabolism*, 41(6), S197-S239.

Prochaska, J. O. (2008). Multiple health behavior research represents the future of preventive medicine. *Preventive medicine*, 46(3), 281-285.

Rai, J., Predy, M., Wiebe, S. A., Rinaldi, C., Zheng, Y., & Carson, V. (2023). Patterns of preschool children's screen time, parent-child interactions, and cognitive development in early childhood: a pilot study. *Pilot and Feasibility Studies*, 9(1), 39.

Reynaud, E., Vecchierini, M. F., Heude, B., Charles, M. A., & Plancoulaine, S. (2018). Sleep and its relation to cognition and behaviour in preschool-aged children of the general population: A systematic review. *Journal of sleep research*, 27(3), e12636.

Romero-López, M., Pichardo, M. C., Justicia-Arráez, A., & Bembibre-Serrano, J. (2021). Reducing aggression by developing emotional and inhibitory control. *International Journal of Environmental Research and Public Health*, 18(10), 5263.

Sampasa-Kanyinga, H., Colman, I., Goldfield, G. S., Janssen, I., Wang, J., Po-dinic, I., ... & Chaput, J. P. (2020). Combinations of physical activity, sedentary time, and sleep duration and their associations with depressive symptoms and other mental health problems in children and adolescents: a systematic review. *International Journal of Behavioral Nutrition and Physical Activity*, 17(1), 1-16.

Spencer, R. M. (2021). The role of naps in memory and executive functioning in early childhood. *Advances in child development and behavior*, 60, 139-158.

Stamatakis, E., Rogers, K., Ding, D., Berrigan, D., Chau, J., Hamer, M., & Bauman, A. (2015). All-cause mortality effects of replacing sedentary time with physical activity and sleeping using an isotemporal substitution model: a prospective study of 201,129 mid-aged and older adults. *International Journal of Behavioral Nutrition and Physical Activity*, 12(1), 1-10.

Tandon, P. S., Klein, M., Saelens, B. E., Christakis, D. A., Marchese, A. J., & Lengua, L. (2018). Short term impact of physical activity vs. sedentary behavior on preschoolers' cognitive functions. *Mental Health and Physical Activity*, 15, 17-21.

Templ, M., Hron, K., & Filzmoser, P. (2011). robCompositions: an R-package for robust statistical analysis of compositional data. *Compositional data analysis: Theory and applications*, 341-355.

Tremblay, M. S., Carson, V., Chaput, J. P., Connor Gorber, S., Dinh, T., Duggan, M., Faulkner, G., Gray, C. E., Gruber, R., Janson, K., Janssen, I., Katzmarzyk, P. T., Kho, M. E., Latimer-Cheung, A. E., LeBlanc, C., Okely, A. D., Olds, T., Pate, R. R., Phillips, A., Poitras, V. J., ... Zehr, L. (2016). Canadian 24-Hour Movement Guidelines for Children and Youth: An Integration of Physical Activity, Sedentary Behaviour, and Sleep. *Applied physiology, nutrition, and metabolism = Physiologie appliquée, nutrition et métabolisme*, 41(6 Suppl 3), S311-S327.

- Tsai, C. L. (2009). The effectiveness of exercise intervention on inhibitory control in children with developmental coordination disorder: Using a visuospatial attention paradigm as a model. *Research in developmental disabilities*, 30(6), 1268-1280.
- Van den Boogaart, K. G., & Tolosana-Delgado, R. (2008). “Compositions”: a unified R package to analyze compositional data. *Computers & Geosciences*, 34(4), 320-338.
- WANG, J., & CHEN, T. Y. (2012). Inhibitory control and higher cognitive functions. *Advances in Psychological Science*, 20(11), 1768.
- Wang, L. F. (2013). Preschool Children’s Emotional Regulation and Inhibitory Control. *Studies in Early Childhood Education*, (03):56-62. [王玲凤. (2013). 幼儿情绪调节与“冷”“热”抑制控制的发展特点. 学前教育研究, (03):56-62.]
- Wu, H. J. (2018). *The Study of the Characteristics and Influencing Factors of Physical Activity among Preschool Children(3-6year)* (Unpublished master’s thesis). Air Force Medical University, Xi’an. [吴海军. (2018). 学龄前儿童 (3-6 岁) 体力活动特征与影响因素研究 (硕士学位论文). 中国人民解放军空军军医大学, 西安.]
- Wu, X., Tao, S., Rutayisire, E., Chen, Y., Huang, K., & Tao, F. (2017). The relationship between screen time, nighttime sleep duration, and behavioural problems in preschool children in China. *European child & adolescent psychiatry*, 26(5), 541–548.
- Yu, C. C., Chen, C. Y., Muggleton, N. G., Ko, C. H., & Liu, S. (2022). Acute exercise improves inhibitory control but not error detection in male violent perpetrators: an ERPs study with the emotional stop signal task. *Frontiers in human neuroscience*, 16, 796180.
- Zelazo, P. D., Carlson, S. M., & Kesek, A. (2008). The development of executive function in childhood. In C. A. Nelson & M. Luciana (Eds.), *Handbook of Developmental Cognitive Neuroscience* (2nd ed., pp. 553-574). MIT Press
- Zhang, T., & Li, H. J. (2020). Application Prospects of Compositional Data Analysis Method in Physical Activity and Health. *China Sport Science*, (09),74-82+97. [张婷, 李红娟. (2020). 成分数据分析方法在身体活动与健康研究领域的应用展望. 体育科学, (09),74-82+97.]
- Zhang, T., Li, H. J., Zhang, Z. H. & Gao, Y. H. (2023). A systematic review of the association between 24-hour movement behavior and obesity in children and adolescents. *Chinese Journal of School Health*, (01):23-27. [张婷, 李红娟, 张翌华, 郜艳晖. (2023). 儿童青少年 24 h 活动行为与肥胖关联的系统评价. 中国学校卫生, (01):23-27.]
- Ziereis, S., & Jansen, P. (2015). Effects of physical activity on executive function and motor performance in children with ADHD. *Research in developmental disabilities*, 38, 181-191.

Note: Figure translations are in progress. See original paper for figures.

Source: ChinaXiv — Machine translation. Verify with original.