Working Memory, Sustained Attention, and Physical Activity: An intraindividual study

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Highlights

Summary

1. The intraindividual study found that working memory and sustained attention are stable over time but there are individual differences in the relationship between working memory and sustained attention
2. Increased MVPA on the day before was followed by decreased working memory the next day
3. Increased self-reported exercise was linked to higher sustained attention but this was not supported by objective MVPA data
4. Activity needs to be increased in PE lessons and there is a need for teachers to recognise individual dips in trait-working memory and trait-sustained attention

Abstract

Objective: Experimental studies show small to moderate effects of both acute and regular physical activity on executive functions, these being strongly associated with academic performance at school. In order to understand the naturally occurring associations between primary school-aged children's working memory (WM), self-reported concentration, and physical activity (PA), 35 children (M_{age} = 9.8 years, range = 7.4 - 11.6 years old) in Years 3-6 of primary school took part in a two-week long intraindividual study.

Method: Participants wore an accelerometer wristband throughout the study, and carried out a working memory task (digit recall) and completed a sustained attention measure each morning and afternoon, giving 517 time-points nested in 4-10 school-days (M_{obs} = 15.8 situations, n_{obs} = 4-18).

Results: Using multilevel structural equation models (MSEM) we found that working memory was stable across time (within-person *b* = 0.29) and trait-like (*ICC*s = 0.58). Across situations, state working memory was higher later in the calendar week. Acute moderate to vigorous physical activity (MVPA) was not associated with state-working memory, but exertion of a higher level of MVPA than usual the previous day was associated with lower state-working memory the following day. Trait-sustained attention (across the two weeks) predicted higher trait-working memory and older students outperformed younger students.

Conclusions: Implications for timing and intensity of students' physical activity in educational settings is discussed.

Keywords: physical activity; working memory; sustained attention; intraindividual; ecological momentary assessment

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Introduction

While much previous research on associations between physical activity, academic performance, and sustained attention has either taken place in the laboratory, or in cross-sectional studies, we were interested in the naturally unfolding day-to-day, situation-to-situation process perspective. It is in this immediate micro-context that teachers encounter children, some children alert and full of energy and ready to go, some distracted or feeling stuck, some stable in their activities and outcomes from one lesson to another, others more variable. To this end we investigated the associations between situation-specific working memory (working memory, using digit span as an index of working memory and as a proxy for academic performance), self-reported sustained attention, and acute physical activity (as an index of PA prior to the lesson in which they did the working memory tasks and reported their sustained attention).

Working Memory and Academic Performance

Executive functioning encompasses multiple mental abilities which are prerequisites for academic success, including working memory, inhibitory control, and cognitive flexibility (Miyake et al., 2000; Diamond, 2013). Children's academic success is associated with positive engagement in learning, confirmed in numerous lines of research (Martin & Dowson, 2009). Both stable child characteristics (e.g. executive functioning) and situational states (e.g. sustained attention) can influence learning and academic performance with working memory having a particularly strong association (Dirk & Schmiedek, 2016; Swanson & Alloway, 2012). Sustained attention has links to and is required for executive functioning skills and the two concepts are closely related and it is suggested that the brain areas implicated in these processes may overlap (Harvey, 2019; Eriksson, Vogel, Lansner, Bergström, & Nyberg, 2015; Helton & Russell, 2015). With regards to sustained attention, children's self-rated and teacher-rated sustained attention is also associated with academic performance, academic functioning and a lower level of inattention (Becker, Luebbe, & Joyce, 2015). Children's

self-reported situation-specific academic functioning (e.g. competence beliefs, motivation, perceived difficulty) and self-reported cognitive engagement is associated with teacher-reported student engagement and observed on-task behaviour respectively (Malmberg & Martin, 2019; Heemskerk & Malmberg, 2020).

Physical Activity and Working Memory

Physical education (PE) classes are compulsory in school yet, in the UK (Beale et al., 2021) a mere 23.8% of allocated PE time is spent in MVPA, resulting in 0.7% of pupils achieving their 30 minute activity threshold. Research indicates that working memory is likely associated with habitual physical activity (Sibley & Etnier, 2003; Davis et al., 2011; Kamijo et al., 2011; Haverkamp et al., 2020; Verburgh, Königs, Scherder, & Oosterlaan, 2014). Other experimental studies found moderate effects of acute physical activity on executive functioning ($ES = 0.57$; (Verburgh et al., 2014)), and weaker effects on working memory ($ES = 0.14$; (Haverkamp et al., 2020), 2020), but less is known about the effects of physical activity on working memory of primary school aged children during ordinary school days over time. Furthermore, moderate physical activity and increased cardio-respiratory fitness was associated with better working memory in pre-adolescent children (Kamijo et al., 2011) and increased working memory scores as a result of high doses of MVPA (Ishihara & Mizuno, 2018). Conversely (Sjöwall, Hertz, & Klingberg, 2017) (2017) found no improvement in working memory skills after a two-year physical activity intervention for primary school-aged children. Furthermore, low effect sizes were found for the effect of acute exercise on working memory $ES = 0.14$) (Verburgh et al., 2014) . Although studies investigating the momentary fluctuations in working memory are rare (but see Dirk and Schmiedek, 2016), physical activity has been found to predict greater on-task behaviour following high intensity PE lessons (Heemskerk, Lubans, Strand, & Malmberg, 2019) which may lead to improved educational outcomes. However, it is unclear whether acute physical activity or habitual physical activity are more closely associated with children's academic functioning.

One explanation of the varied effects of physical activity intensity is that MVPA

and working memory have an inverted-U relationship. There may be an optimum limit for intensity and/or amount of MVPA at which cognitive skills peak and above and below that level they decline (Tomporowski, 2003; Lambourne & Tomporowski, 2010). The negative effect of high MVPA has also been replicated with academic achievement and maths performance, indicating that there may be a consistent effect of physical activity on cognitive functioning (van Dijk, de Groot, Savelberg, van Acker, & Kirschner, 2014). However, increased physical activity levels have been reported to offset the mental fatigue causing decline in working memory task performance over the day when compared to sedentary adults (Bugg, DeLosh, & Clegg, 2006) with similar findings reported in school-aged children (Chaddock-Heyman, Hillman, Cohen, & Kramer, 2014; Rasberry et al., 2011). The literature indicates a positive association between physical activity and working memory where a meta-analysis has shown that working memory is the most sensitive to physical activity (Álvarez-Bueno et al., 2017), although there are factors to be considered, such as physical activity timing, intensity level and characteristics of the child.

The Current Intraindividual Study

There is growing interest in the analyses of process data (e.g. intraindividual, intensive longitudinal, diary, micro-analytical, ecological momentary assessment) in health, psychological and educational research (Hamaker & Wichers, 2017; Heemskerk & Malmberg, 2020; Malmberg, 2020; Schmitz & Skinner, 1993; Schmitz, 2006). An intraindividual focus reduces retrospection-bias and enhances contextual closeness (as events are reported close in time to the experience of events), and enables a combination of self-report and objective ambulatory data. We expand previous intraindividual studies in two ways. Firstly, previous studies of associations between working memory, engagement and educational performance have been based on self-reported working memory, or aggregated recorded physical activity across a time-frame (e.g. a week). Therefore we investigated minute dynamics between situation-specific working memory and sustained attention. Secondly, previous intraindividual research has been critiqued

for using subjective situation-specific indicators. We employed similar approaches to that of recent research of intraindividual variability of working memory (Dirk & Schmiedek, 2016; Galeano Weber, Dirk, & Schmiedek, 2018) by using repeated measures of working memory and sustained attention to evaluate situation-specific effects using objective data. In this research, we applied appropriate multilevel structural equation models, enabling us to model *both* situations and persons, and situation-specific and person-specific predictors of these. State-variables refer to situation-specific variables at the within-level model and trait-variables refer to individual means at the between level, aggregated from the within-level.

Research Questions

The aim of this study was to investigate the dynamic relationships between situation-specific (acute) physical activity, habitual physical activity, sustained attention and working memory. We posed the following research questions:

(1) How stable is state-working memory over time?

(2) Does state-attention predict state-working memory, and trait-attention predict trait-working memory?

(3) How do situational characteristics (time of day, day of week), acute physical activity and daily physical activity predict working memory?

(4) How do child-characteristics (age, sex, self-reported physical activity, total MVPA) predict trait-working memory?

Method

Sample

A total of 38 children from four classes in one primary school in England participated in the study. Parents/guardians gave informed consent for participation and children provided verbal assent. One child withdrew, and two did not have valid accelerometer recordings, giving a final study group of 35 participants (54% girls) aged between 7.6 years and 11.4 years (M = 9.8 years, SD = 1.0 years). The school is in a

first-quintile area according to the Index of Multiple Deprivation, indicating a low level of deprivation.

Procedure

Each school day in the morning (approx 10:30) and again in the afternoon (approx 14:30) they completed a sustained attention questionnaire and a working memory task (forward digit recall). The STROBE reporting guidelines were used (Von Elm et al., 2007). Data were collected within the framework in relation to availability of students in school. The data-collection that was possible for one person (the first author) within this three-week window was certainly maximized. Ethics were cleared at the first author's institution (PREC 19-050). The data-collection took place in 2019 in Spring, so COVID-19 was not a concern at that time.

Instruments

Physical Activity Questionnaire for Children (PAQ-C) The PAQ-C is based on the activities children carried out in the previous school week (Crocker, Bailey, Faulkner, Kowalski, & McGrath, 1997). The measure has strong test-retest reliability in European populations (ICC = 0.96) (Benítez-Porres et al., 2016) as well as good reliability when compared to accelerometer data (ρ = 0.44-0.55) (Voss, Dean, Gardner, Duncombe, & Harris, 2017). An individual's PAQ-C score that was used in the model was calculated as an average of responses to all questions and scores range between 1-5, where 1 = low physical activity and 5 = high physical activity. The internal consistency (Cronbach's α) was $M_\alpha = 0.82$, indicating high reliability for this study.

Accelerometer wristband Axivity AX3 accelerometer wristbands were worn on the non-dominant wrist, measuring tri-axial movement in relation to gravity. Axivity AX3 accelerometers have proven accuracy in validation studies (Clarke et al., 2017; Feng, Wong, Janeja, Kuber, & Mentis, 2017). Following methods suggested in other research Phillips, Parfitt, and Rowlands (2013) we calculated a range of situational and daily aggregates. To account for acute effects of physical activity, we calculated morning and afternoon aggregate values of moderate to vigorous physical activity (MVPA) as a

proportion of the time, two hours prior to the digit recall and self-report. We also aggregated the level of MVPA the previous day, and over the whole 12 day research period. Accelerometry-based physical activity data was split into one-second epochs and divided further into time-segments as per school's schedule (see table 1).

Forwards Digit Recall Test (FDRT) The FDRT was selected to measure working memory due to its specificity to working memory in children (St Clair-Thompson, 2009) and high test-retest reliability (Gathercole, Brown, & Pickering, 2003). From a small pilot study, the digit recall took less than 10 minutes which allowed the CCI to also be completed in a suitable amount of time to be administered twice a day (morning and afternoon) for ten days. This was an acceptable data-collection solution also for the school/teachers. The FDRT consists of question sets made up of six trials which increase by one digit in each set, e.g., set 1 "2 5", set 2 "3 6 2", set 3 "4 7 1 3", set 4 "3 1 7 4 5", set 5 "4 6 1 5 7 2" up to sets with eight digits. When we split the dataset into 18 time-segments (nine days with two time-points per day) average internal consistency (Cronbach's α) was $M_\alpha = 0.94$, $SD_\alpha = 0.03$. Item Response Models (IRT) suggested appropriate structural validity of the test. Digit recall was administered to children by the first author in a school in small groups who worked in silence. The outcome being measured was the total number of digit sets recalled, abiding by the scoring process of the FDRT which ceases to count digits recalled after four of incorrect responses.

Child Concentration Inventory As a measure of sustained attention we used the Child Concentration Inventory (CCI) (Becker et al., 2015), which includes three sub-scales: slow (e.g., "delayed in tasks"), sleepy ("drowsy"), and day-dreaming ("lost in thoughts"). Children reported on four-point scales (0 = not at all, 1 = just a little, 2 = pretty much, 3 = very much) to what extent they experienced each of the states. The higher-order factor of the instrument was used as it had the best convergent and discriminant validity (Becker et al., 2015). The score was made up of an average of all 14 items from all sub-scales where each answer is given a score (0,1,2,3) and reverse scoring is used for negatively worded questions and this average was used in the model (Cronbach's α) was $M_\alpha = 0.90$, $SD_\alpha = 0.04$).

Design and Analysis

Upon inspection of missing data showed that 2.1% of data-points were missing, we carried out a multilevel imputation in Mplus 8.5 (Muthén & Muthén, 1998-2017) creating a complete datamatrix for analysis. We specified multilevel structural equation models, with of $n_{ti} = 517$ time-points (t) nested in $n_i = 35$ children (i). In an initial variance component model we estimated the proportion of variance between children (ICC = 0.58, 90% credibility interval (C.I.) [0.48, 0.68]). In order to investigate the stability of working memory across time, we regressed working memory at Time T (the concurrent time-point) and at Time T-1 (the previous time-point; see model 1 in Fig 1. We then, in model 2, included *state*-sustained-attention as a predictor of state-working memory at the within-level, and *trait*-sustained-attention as predictor of trait-working memory at the between-level. In model 3, we included situation-specific predictors (time-of-day, day-of-week, acute physical activity and physical activity the previous day). All within-level predictors were centered within clusters (CWC) in order to interpret these as effects of individuals deviating from their own mean. In the fourth model we included grand-mean-centered child-characteristics (age, sex, self-reported physical activity, total MVPA) as predictors of trait-working memory.

We used the Bayesian estimator with diffuse priors (Asparouhov & Muthén, 2019) for all models. Bayesian statistics estimate the probability of the parameter given the data. It does not rely on large sample theory, and as such is appropriate also for smaller samples (Muthén & Asparouhov, 2012; Hox, Van de Schoot, & Matthijsse, 2012; Zitzmann, Lüdtke, Robitzsch, & Marsh, 2016). Quality of convergence and model fit was checked through auto-correlation plots, trace-plots, and posterior distribution plots. As indices of model fit we report the Posterior Predictive P-Value (PPP, with values close to 0.5 indicating good model fit), the Deviance Information Criterion (DIC), and the maximum Potential Scale Reduction (PRS, with values ≤ 1.05 indicating appropriate convergence), and 90% credibility intervals for parameter estimates from the posterior distribution are reported (Gelman et al., 2013).

Results

Table 1

Descriptive statistics for situations nested in children

Situations										
Variable	1.	2.	3.	4.	5.	n	M/%	SD	Min	Max
1. State digit-recall						517	25.15	6.38	3.00	43.00
2. State sustained attention [1]	**.24**					494	2.47	0.62	0.00	3.00
3. Time of day [2]	.02	-.03				517	48.0			
4. Day of week [3]	**.10**	-.03	.03			517	0.22	1.33	-2.00	2.00
5. MVPA 2 hours prior [4]	.03	-.05	**.25**	.02		491	0.10	0.07	0.00	0.45
6. MVPA previous day	-.07	-.02	-.01	.08	**.30**	457	0.08	0.04	0.00	0.20
Children										
Variable	7.	8.	9.	10.	11.	n	M/%	SD	Min	Max
7. Trait digit-recall						35	25.14	4.81	13.72	34.29
8. Trait sustained attention	**.33**					35	2.47	0.69	0.63	3.00
9. Age	**.42**	-.03				35	9.79	1.06	7.75	11.50
10. Sex [5]	-.09	.25	-.23			35	54.3			
11. PAQ-C [6]	.17	**.38**	-.05	-.14		35	3.49	0.82	2.00	5.00
12. MVPA week	.03	-.07	.05	**-.43**	.14	35	0.08	0.02	0.04	0.14

Note: [1] The total score (14 items) from the Child Concentration Inventory (Becker et al., 2015), [2] 0 = approx 10.30 a.m. , 1 = approx 14.30 p.m. [3] -2 = Monday, -1 = Tuesday, 0 = Wednesday, 1 = Thursday, 2 = Friday; [4] MVPA = moderate to vigorous physical activity, [5] 0 = boy, 1 = girl. [6] = physical activity Questionnaire for Children. Pairwise correlation coefficients in **bold** indicate that the credibility interval did not contain zero. All estimates are based on the raw data (IBM-SPSS 26).

Before modelling we report on noteworthy associations not included as directional effects in the models and the summary statistics of the physical activity data. At the situation-level (i.e., time-points) acute MVPA (i.e., 2 hours prior to working memory) was higher in the afternoons (r = .25), and acute MVPA positively associated with

MVPA the previous day (r = .30). It is possible that higher afternoon activity could reflect both school timetabling where PE lessons were normally scheduled for the afternoon but also participation in after-school and extracurricular activities in children in this age group. In terms of the finding linking the previous day's MVPA, the relative consistency and relationship between periods of physical activity in this study could be explained by the activitystat hypothesis (Gomersall, Rowlands, English, Maher, & Olds, 2013) and also reflect that the physical activity measures could not show a persistent increase as this would be unsustainable. At the between-level (i.e., child-level) self-reported trait-sustained attention was positively associated with self-reported physical activity (PAQ-C). Sustained attention and physical activity have been linked in previous research, however when considering measures to include as directional effects in the model, the correlation between the subjective measures of self-reported physical activity was lower than between the objective measures. Finally, boys were more physically active than girls (sex and weekly MVPA, r = -.43) which is a widely observed pattern and has been linked to lower fitness, coordination and competence in physical activity for females (Telford, Telford, Olive, Cochrane, & Davey, 2016). In a larger sample it may be interesting to understand if this corresponds to tangible differences in the impact on working memory between sexes. On average participants did one hour and 11 minutes of MVPA per day per child. MVPA was 60+ minutes on 61.8% of the observed days. They met the government target of 60+ minutes/day on 6.28 days on average across the 11 days (including one weekend).

In the first model (see left in Fig 1) we found that working memory was stable over time (= 0.29, 90% C.I. [0.21, 0.37]). In the second model state-sustained attention did not predict state-working memory (= 0.01, 90% C.I. [-0.06, 0.08]), but trait-sustained attention predicted trait-working memory (= 0.38, 90% C.I. [0.10, 0.63]). In the third model, day-of-week (i.e., later in the week) predicted higher state-working memory (= 0.12, 90% C.I. [0.04, 0.19]), and physical activity the day before predicted lower state-working memory (= -0.09, 90% C.I. [-0.16, -0.02]). In the final model age predicted trait-working memory (= 0.40, 90% C.I. [0.16, 0.58]), and

an effect of acute MVPA on state-working memory (β = .07, 90% C.I. [0.01, 0.14]).

In supplementary analysis (see [web-address to be included]), in which we also accommodated unequal time-lags between the measurement points by using a time-series analysis in the dynamic structural equation modelling (DSEM) framework, we replicated the magnitude of all fixed effects, except for the effect of acute MVPA on working memory at the within-level.

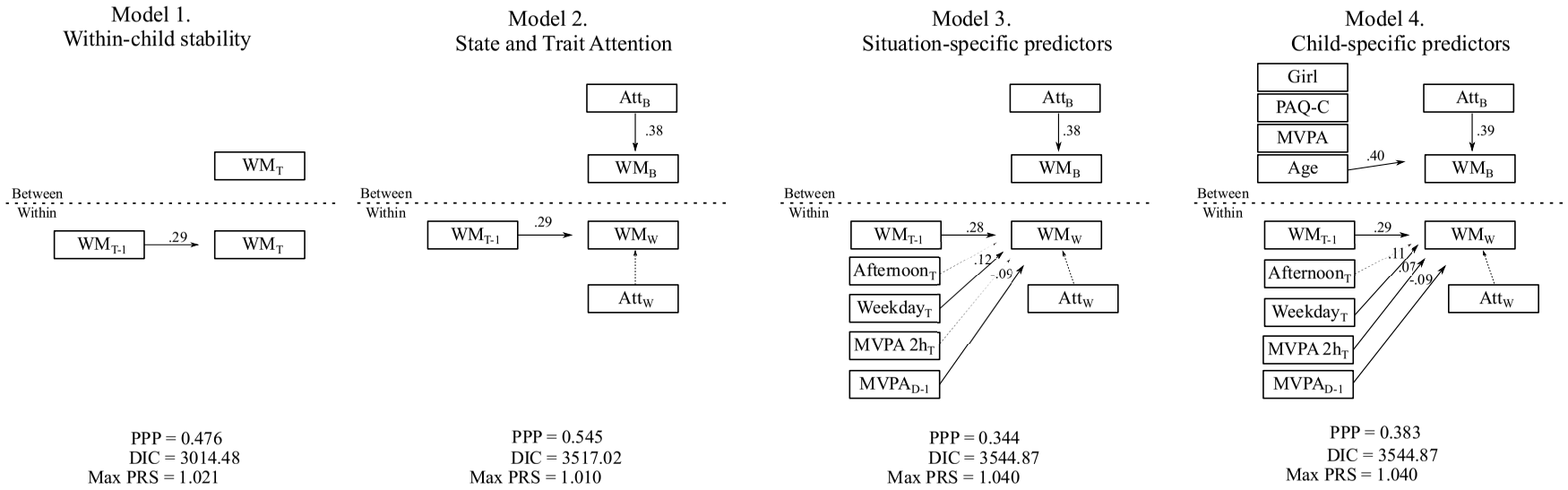

Figure 1. Multilevel Structural Equation Models (MSEM) of associations between working memory and sustained attention, and effects of situation-specific and child-characteristics.

Note: WM = working memory (digit recall), Att = sustained attention (Child Concentration Inventory, W = within-level variable, B = between-level variable, T = concurrent time-point, T-1 = previous time-point. Time-points (within) were nested within children (between). Standardized parameter estimates from posterior distribution are from Mplus 8.5. 90% credibility intervals contain are presented in the text.

Discussion

The aim of this intraindividual study was to investigate the dynamic relationships between situation-specific (acute) p hysical a ctivity, h abitual p hysical a ctivity, sustained attention and working memory, posing four research questions.

Daily dynamics of working memory and sustained attention

While sustained attention clearly matters for working memory, which in turn is central for academic engagement and performance, typical educational studies have made use of pre-test-post-test, cross-sectional, or longer-term longitudinal assessments of working memory. We investigated the within-child dynamics and found working memory stable from morning to afternoon, and afternoon to the following morning and the same was true for sustained attention.

We found that working memory was higher later in the week which can be interpreted in different ways. We suggest two potential explanations for the findings observed here. Either the cycle of cognitively stimulating activities children are asked to do accumulate towards the end of the week. Alternatively, children may improve their performance on the digit recall task due to the repeated practice on the tasks. This finding suggests that school timetables could be structured in a way that maximises academic performance, as the links between working memory and academic success are well established (Swanson & Alloway, 2012).

Sufficient recuperation after physical activity?

When children did more MVPA than their own average, the previous days' MVPA was associated with lower working memory. Alternatively, when children did less than their average MVPA the previous day their working memory was higher. The latter finding mirrors results from studies which have found that individuals have a limit of physical activity whereby if they are over-exerted, their cognitive performance drops (McMorris & Hale, 2012). The inverted-U curve has been previously established (i.e., "too much" and "too little" physical activity has a negative effect). If our daily-lagged

MVPA picks up PE lessons (e.g., if it is the only physical activity some children do during the week), these children would need to be given opportunity to recuperate the following day. Alternative frameworks such as embodied cognition could also be valuable for future research investigating in-situ fluctuations in cognitive performance to further understand the level of recuperation needed after physical activity and the timing of the activity (Pontifex, Gwizdala, Parks, Pfeiffer, & Fenn, 2016).

This optimum level of physical activity has interesting applications when considering the provision of PE lessons in a school setting which are discussed later. The present research also found no immediate effect of MVPA on working memory, unlike inhibitory skills which has been documented in previous research (Drollette et al., 2014). This suggests that working memory may not be affected by immediate MVPA in the same ways as other EF skills are, echoing the suggestion that working memory has a stable and trait-like manifestation in primary-school children rather than a powerful situational influence.

Trait-sustained attention predicts trait-working memory

One important finding from our study is that situation-specific sustained attention did not predict situation-specific working memory ($\beta = 0.02$), but trait-sustained attention (i.e., average sustained attention across the two weeks) did predict trait-working memory (i.e., average working memory across the two weeks) ($\beta = 0.38$). The findings demonstrate that children's performance in situations is relatively unrelated to their situational sense of sustained attention, in some instances they can recall digits well even though they are not concentrated, or in other instances recall digits poorly even though they are concentrated. This finding replicates the link between working memory and sustained attention as observed in neurological research and provides a further insight into the type of sustained attention to focus on in a school setting in order to capitalise on working memory performance (Helton & Russell, 2015; Eriksson et al., 2015).

Child-characteristics, working memory and sustained attention

Consistent with previous findings older children had more accurate working memory (Camerota, Willoughby, & Blair, 2019), but there was no association between age and trait-sustained attention (Becker et al., 2015). While children who reported being more physically active also felt more focused on average, this was not corroborated by their MVPA. Surprisingly, overall MVPA was not associated with digit recall. The implications of the inverted-U curve may suggest that there is a not a positive relationship due to over-exertion and too much physical activity being carried out by participants. However, similar to the findings across Europe and England (van Stralen et al., 2014; Beale et al., 2021), many children do not complete sufficient exercise to elicit potential increases in working memory that have been shown in other research. As this study reflected a real-life account of normal activities, it highlights that children naturally do not substantial physical activity, which explains why in other studies that used laboratory methods to ensure that participants do enough MVPA have found significant effects of MVPA on working memory. However, individual differences are an important consideration for this research question, as the individual effect of physical activity will vary between participants due to their typical exercise and activity levels and current working memory ability.

Limitations

There were four limitations of our study. First, although the within-child data was relatively rich, the number of participants was small (Schultzberg & Muthén, 2018). Second, we did not have the opportunity to collect more information to use as covariates, e.g., children's academic performance, height and weight, and socioeconomic background. Third, the sample was recruited in one primary school in England. Our findings would need to be replicated in a larger, more diverse sample with access to a wider variety of demographic and physiological variables to validate the findings from this study. In future it would be valuable to utilise mobile devices to conduct more frequent momentary assessments of participants which would help provide more

instinctual responses. Also, by collecting data on children's academic performance it may be possible to draw further links between physical activity, sustained attention and academic performance as this is a concern for schools and families. This would provide further insight into a potential relationship between these factors and what, if any, physical activity interventions could be integrated into PE lessons to improve academic performance.

Applications

We found substantive variability in children's working memory and sustained attention and an association between these and acute and habitual physical activity.

Aside from the insight into the varied impact of physical activity on working memory this research provides, there are implications for educational policy. The findings of our study indicate that children reached 60+ minutes of MVPA on 61.8% of days and on average had one hour and 18 minutes (range of 39 minutes - 2 hours 9 minutes) of MVPA each day. Although these results are encouraging and indicate that this sample of children met the guidelines in some cases, the range in daily physical activity still indicates that the current guidance is a challenging goal for some individuals and highlights the need for ensuring that PE lessons in school will contribute to this amount. These findings reflect similar results in other large studies of activity in children (Álvarez-Bueno et al., 2017; Beale et al., 2021). Similar considerations for adapting PE lessons have been made in research which found that only 23.8% of PE time is spent in MVPA in UK schools (Beale et al., 2021) and that particular focus should be given to increasing overall activity.

There have been suggestions that the structure of the school day may be protective against further damage to physical health due to the forced periods of exercise and reduced screen time, as proposed by the structured days hypothesis (Brazendale et al., 2017). However the time allocated for physical activity at school is minimal and does not guarantee periods of MVPA (Beale et al., 2021). Although it seems difficult to see that school timetabling can allow for more PE lessons to be included, this observed

inactivity suggests educational policy needs to be updated regarding PE in schools to increase the time spent and intensity of exercise in lessons to capitalise on the opportunity to ensure that all children are on their way to reaching the guidelines. As physical activity is mandated in primary schools in England, the school setting could be a useful location to target interventions to encourage greater physical activity as it is a supervised environment, rather than attempting community-based interventions.

Also, given the situational variability in working memory and sustained attention, it appears that children who have relatively high trait-working memory or trait-sustained attention have their dips when they are tired, disengaged, or off-task. Likewise children with relatively lower trait-working memory or trait-sustained attention have their peaks when they are switched on, engaged and on-task (Malmberg & Martin, 2019). An important task for teachers is to recognise such highs and lows, capitalise on teachable moments when they occur, and allow for rest and recuperation when needed. Within a broader emerging field of personalized learning (Dockterman, 2018; Tetzlaff, Schmiedek, & Brod, 2021), important intraindividual states for educators and instructors to recognize are: an increased awareness of individual children's need to rest and recuperation, as well as recognition of their alert and engaged moments, and adaptation of meaningful tasks for such situations. This method of more personalised teaching may become popular with more insight into daily variations in cognitive skills from these intra-individual research designs.

Conclusion

In conclusion, this research suggests that there are individual differences in the relationship between working memory and sustained attention. In some cases increased MVPA led to lower working memory scores the next day. The research highlights the need to increase intensity and duration of physical activity of the children in this age group, either in a school or extracurricular setting.

Footnotes

Data Availability

No data are available

Further details on models are available from the second author (withheld).

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Contributions

(withheld) assumed full responsibility for all aspects of the research including design, data collection, analysis, interpretation, drafting and editing the manuscript and approval of the final manuscript and submission. (withheld) and (withheld) contributed to the design of the project, data analysis and interpretation and drafting and editing the manuscript and approval of the final manuscript and submission.

Competing Interests

None declared.

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There was no patient or public involvement in the design, research questions, outcome measures or recruitment to the study.

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Figure

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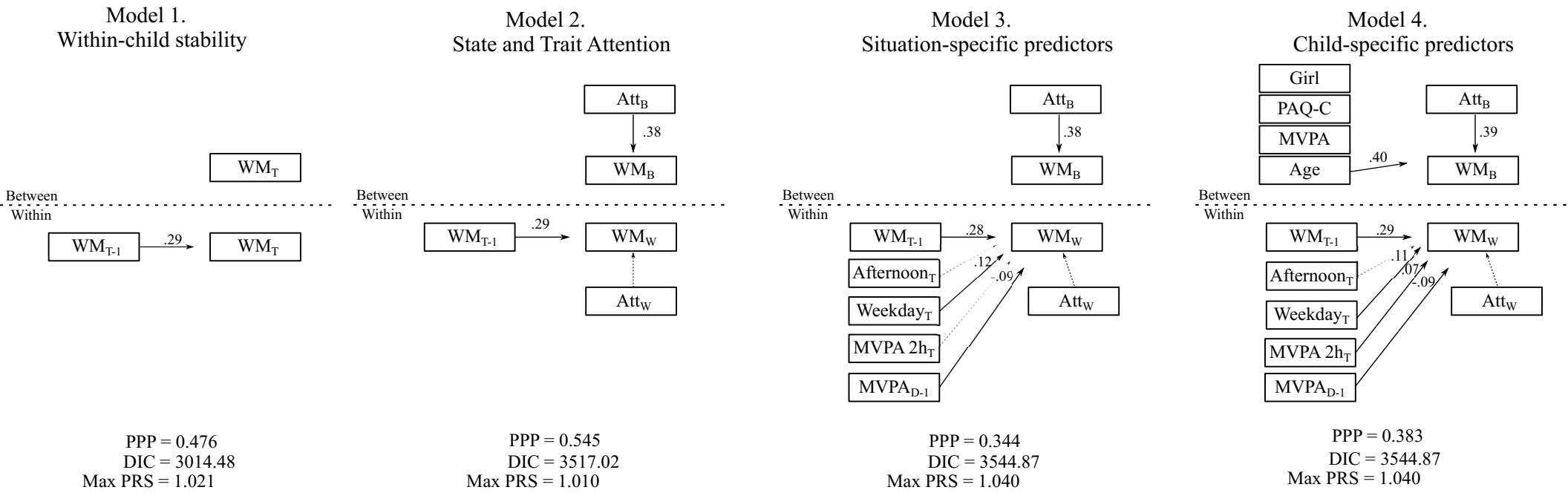

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:
