The Associations between Leisure-Time Physical Activity and Academic Performance: A Twin Study

ABSTRACT

Background Both genetic and environmental influences have been shown to contribute to the association between physical activity and overall academic performance. We examined whether leisure-time physical activity (LTPA) shares genetic and environmental variances between spelling, essay writing, reading aloud, reading comprehension and mathematics in early adolescence. Moreover, we investigated whether genetic polymorphisms associated with physical activity behavior affect these academic skills.

Methods Participants were 12-year-old Finnish twins (n=4356–4370 twins/academic skill, 49% girls). Academic skills were assessed by teachers and LTPA was self-reported. Polygenic scores for physical activity behavior were constructed from the UK Biobank. Quantitative genetic modeling and linear regression models were used to analyze the data.

Results The trait correlations between LTPA and academic skills were significant but weak (r=0.05–0.08). The highest trait correlation was found between LTPA and mathematics. A significant genetic correlation was revealed between LTPA and essay writing (r_A=0.14). Regarding polygenic scores of physical activity, the highest correlations were found with reading comprehension, spelling and essay writing, but these results only approached statistical significance (p-values 0.09–0.15).

Conclusions Our results suggest that reading and writing are the academic skills that most likely share a common genetic background with LTPA.

There is a strong body of research on the association between physical activity and academic performance[1-4]. However, recent systematic reviews have concluded that the levels of associations between physical activity and different academic skills vary greatly[5,6]. The strongest evidence for the association with physical activity was found for mathematics by Singh et al. (2019)[5], while Haverkamp et al. (2020)[6] only demonstrated a significant effect of physical activity on academic skills within the language domain. In addition to these conflicting association findings within different academic skills, the direction of the potential association and the nature of causality between physical activity and academic performance has also remained under debate without any clear results on whether the association constitutes a causal effect[7-10].

Previous studies have also shown that similar to overall academic performance, mathematic- and reading-specific academic skills are highly heritable[11,12]. Moreover, physical activity has been shown to be moderately heritable[13,14]. We have also shown, contrary to the idea of causality, that the association between leisure-time physical activity (LTPA) and grade point average can partly reflect overlapping genetic and familial influences[7]. Therefore, a better understanding of common genetic and familial background that potentially account for the associations between physical activity and different academic skills would be warranted.

In this study, we aimed to examine to what extent LTPA and academic performance in spelling, essay writing, reading aloud, reading comprehension and mathematics share genetic and environmental influences in early adolescence using genetic twin modeling and polygenic scores (PGS). By using these two different methods, each making different methodological assumptions, we are able to analyze the genetic background of LTPA and academic performance more comprehensively than when relying on only one method.

METHODS

The participants of this study were drawn from the FinnTwin12 study, which is a population-based longitudinal study of health and behavior in Finnish twins born in 1983–1987[15]. The twins and their parents completed study questionnaires on health, behavior, lifestyle and social/interpersonal environments when the twins were 11–12 years old (age range 10.8–12.3 years). The response rate was 90%. Most of the twins were in the same class and had the same teacher who usually had a long-term teaching relationship with the twins. The teachers assessed the twins' behavior and academic skills at school. In this study, we had data available on LTPA and academic skills from 4356 to 4370 twins per skill (51% boys and 49% girls) including 2102 full twin pairs. DNA was extracted from blood and saliva samples collected when the twins were young adults (mean age 24.4 years). Within the sample, 32% of the twins were monozygotic, while 31% were same-sex dizygotic and 31% were opposite-sex dizygotic twins.

ASSESSMENT OF ACADEMIC PERFORMANCE

The teachers of the twins assessed spelling, essay writing, reading aloud, reading comprehension and mathematics when the twins were at the mean age of 11.4 years with the following question specifically tailored for the study: "Please, evaluate a twin's performance in the following academic skills compared to the average pupil in your class?". The response options were categorized as follows: 1) clearly below the average, 2) slightly below the average, 3) average, 4) slightly above the average, and 5) clearly above the average.

ASSESSMENT OF LEISURE-TIME PHYSICAL ACTIVITY

Twins self-reported their LTPA based on a structured question on the frequency of LTPA excluding physical education classes at school: "How often do you exercise in your leisure time?". There were five response options: 1) not at all 2) two to three times in six months, 3) two to three times a month, 4) two to three times a week, and 5) just about every day.

DEMOGRAPHIC VARIABLES

The age of the twins was calculated based on their date of birth obtained from the Finnish Population Register Centre and the date of return of the study questionnaire. The sex of the twins was also provided by the Finnish Population Register Centre and cross-checked with the self-reported questionnaire data. The zygosity of the twins was mainly based on measured genotypes. However, there were a few twins who did not have a DNA sample and their zygosity was based on questions on physical similarity at age 11–12. This method has been shown to have high validity in this twin cohort[16].

POLYGENIC SCORES

Genome-wide genotype data were used to produce PGS for physical activity behavior. The PGSs were constructed for self-reported and accelerometer-measured physical activity from the UK Biobank data that is based on the general UK population between ages 40–69[17,18]. The self-reported questions based on the "number of days/week of walked 10+ minutes" ($PGS_{WALKING}$), "number of days/week of moderate physical activity 10+ minutes" ($PGS_{MODERATE}$) and "number of days/week of vigorous physical activity 10+ minutes" ($PGS_{VIGOROUS}$). The accelerometer-measured physical activity based on walking activity ($PGS_{MEASURED\ WALKING}$), moderate intensity activity ($PGS_{MEASURED\ MODERATE}$) and overall activity ($PGS_{MEASURED\ TOTAL}$) was tracked with Axivity AX3 wrist accelerometer over 7

days[19]. Kujala et al. (2020)[20] have reported the details of the genotyping and polygenic scoring.

STATISTICAL METHODS

First, we estimated intra-class correlation coefficients to quantify the degrees to which monozygotic and dizygotic twins resemble each other for LTPA and academic skills (Supplementary table 1). The genetic twin modeling began by decomposing the trait variation in LTPA and academic skills into three components (additive genetic variation (A), shared environmental variation (C), and unique environmental variation (E)) and comparing different univariate models to select the best-fitting model (Supplementary table 2)[21]. Based on the best-fitting univariate model, we estimated genetic and environmental contributions to LTPA and academic skills by sex (Supplementary table 3): the contributions of genetic influences to LTPA were 30% in boys and 17% in girls, whereas the heritability estimates for the academic skills ranged from 64% to 77% in boys and from 53% to 69% in girls. Next, bivariate Cholesky decompositions were conducted to estimate trait correlations between LTPA and academic skills[22]. We further decomposed these trait correlations into genetic and environmental correlations and estimated to what extent the proportions of the trait correlations are explained by genetic and environmental factors. The bivariate Cholesky decompositions were also used to derive a test of causality between these two traits: a causal association should appear as both genetic and environmental correlations[23]. The correlations were initially performed based on the univariate model-fitting results. However, decompositions for boys and girls separately could not be reliably estimated; thus, we present the bivariate Cholesky decomposition results for both sexes as main findings. The findings for boys and girls separately are shown in Supplementary table 4. OpenMx software (version 2.0.1) was used for these quantitative genetic analyses[24].

We used linear regression models to analyze whether the academic skills were associated with genetic susceptibility to physical activity behavior (presented as PGSs). The physical activity–related PGSs and academic skills were scaled to obtain standardized normal distribution with a mean of 0 and standard deviation of 1. The regression models were adjusted for sex and the first 10 genetic principal components to control for population stratification. Because we analyzed twins as individuals, the regression models were controlled for the clustering of twins within pairs because the observations between co-twins may be correlated. We used Stata 14.1 software (StataCorp, College Station, Texas, USA) to produce linear regression models as well as baseline statistics. Descriptive statistics are presented in Supplementary table 5. The means and standard deviations of LTPA and academic skills stratified by zygosity and sex are provided in Supplementary table 6.

ETHICS OF THE STUDY

The ethics committee of the Department of Public Health of the University of Helsinki (Finland), the ethics committee of the Helsinki University Central Hospital District (Finland) and the Institutional Review Board of Indiana University (USA) approved the FinnTwin12 study protocol. The parents of the twins initially provided written informed consent for study participation, but as young adults, the twins themselves provided written informed consent for genetic analyses.

RESULTS

The trait correlations between LTPA and academic skills were positive and statistically significant but weak (from 0.05 to 0.08) (Table 1). The highest trait correlation was found between LTPA and mathematics. Based on the Cholesky decomposition, common genetic in-

fluences statistically significantly contributed to the association between LTPA and essay writing (r_A=0.14), supporting a genetically-influenced mechanism underlying the association. The next highest genetic correlations were found between LTPA and reading aloud as well as between LTPA and mathematics (both r_A=0.11), but these findings did not reach statistical significance. Even though the importance of familial factors in explaining the associations between LTPA and academic skills was highlighted by intra-class correlation coefficients and by the fact that shared environmental influences could not be dropped from the best-fitting final models (Supplementary table 2), no significant shared environmental correlations were found between LTPA and different academic skills. Furthermore, no significant unique environmental correlations between LTPA and academic skills were found.

The associations between genetic susceptibility to physical activity behavior (i.e., PGSs) and academic skills are shown in Table 2. The analyses revealed weak and non-significant associations between the PGSs for physical activity behavior and academic skills: positive within PGSs based on the accelerometer-measured physical activity and mostly negative within PGSs based on the questionnaire-based physical activity. With regard to accelerometer-measured physical activity, the highest associations were found between $PGS_{MEASURED\ WALKING}$ and spelling and essay writing (both r=0.05), but these results only lean toward statistical significance (p=0.13 and p=0.15, respectively). Although many associations related to PGSs based on the questionnaire-based physical activity were even lower than those based on the accelerometer-measured physical activity, the association between $PGS_{VIGOROUS}$ and reading comprehension (r=-0.06) approached statistical significance (p=0.09). The next highest associations regarding the PGSs based on the questionnaire-based physical activity behavior were found between $PGS_{VIGOROUS}$ and spelling (r=-0.05, p=0.15) as well as between $PGS_{VIGOROUS}$ and essay writing (r=-0.06, p=0.15).

DISCUSSION

By using genetically informative twin data, we examined the genetic and familial associations between LTPA and academic skills in spelling, essay writing, reading aloud, reading comprehension and mathematics in early adolescence. Regarding the twin modeling, the most apparent finding to emerge was that all academic skills were positively associated with LTPA. We found the highest association between LTPA and mathematics. However, these observed associations between LTPA and academic skills shared genetic influences to a small extent; only the association between LTPA and essay writing was found to have a significant genetic component. Reading aloud and mathematics showed the next highest genetic correlation with LTPA, but without statistical significance. We found no significant environmental correlations (neither shared nor unique environmental correlations) between LTPA and academic skills.

Contrary to the twin modeling results, PGSs for physical activity behavior were not significantly associated with academic skills – however, the results related to reading comprehension, spelling and essay writing approached a customary level of statistical significance. It is important to note that PGSs were based on age groups older (i.e., 40–69-year-olds) than our study participants (i.e., 11–12-year-olds). This may potentially affect the associations found between PGSs and academic skills. The reality of the associations may be represented more accurately by PGSs based on the accelerometer-measured physical activity than based on the questionnaire-based physical activity because accelerometers may better reflect voluntary physical activity behavior and inherent physical activity abilities of the individual, regardless of the individual's age.

This study supports evidence from previous observations indicating a positive association between LTPA and academic performance[1-3]. We found the highest trait correlation between LTPA and mathematics, which reflects the results of the meta-analysis of Singh et al. (2019)[5]. Moreover, our study confirms the results of the previous studies indicating that LTPA is moderately[13,14] and academic performance highly heritable[11,12,25,26]. We found a statistically significant genetic correlation (r_A=0.14) regarding the association between LTPA and essay writing. This result, along with the non-overlapping shared environmental and non-overlapping unique environmental influences between LTPA and essay writing, challenges the assumption of a potential causal relationship between LTPA and essay writing by indicating that there is a genetic relationship between these two traits (a causal association between LTPA and essay writing should appear as both genetic and environmental correlations). The genetic correlation of 0.14 we found between LTPA and essay writing is also in line with the genetic correlation estimate we found in our previous study between LTPA and grade point average for boys at age 12 (r_A=0.17) when using the same data-set[7]. Overall, our twin modeling and analyses related to PGSs show that reading and writing are the academic skills that most likely share a common genetic background: results are systematic yet not statistically significant regarding all estimates. Speculatively, these common genetic backgrounds might explain the trait correlations found between these traits as well as suggest that reading and writing represent, to a great extent, a grade point average.

In light of our previous study[7], showing that the association between LTPA and grade point average was also partly explained by the overlapping familial environmental influences, it is somewhat surprising that common familial background was not found to exist between LTPA and any academic skill. It is possible that the academic performance data used in the current study did not reliably estimate shared environmental influences: the confidence intervals of

shared environmental correlations are wide, which may indicate that our data are underpowered to decompose shared environmental influences explaining the proportions of the trait correlations between LTPA and academic skills.

We focused on twins' frequency of LTPA, which greatly reflects voluntary behavior. Our assessment may be a restricted picture of the total LTPA, but it still represents twins' physical activity behavior in their leisure time. The validity of physical activity questionnaires used in Finnish twins have been demonstrated[27,28]. Academic skills were reported by teachers. The measurements were not standardized and not totally comparable but teachers evaluated the twins' skills as objectively as possible. In Finland, practically all teachers have undergone Master's level training and schools follow a national curriculum meaning that teachers' evaluations are based on similar principles.

A further limitation is that our study design was cross-sectional. Even though our cross-sectional twin data contain genetic information that can be used to derive a test of causality between leisure-time physical activity and academic skills[23,29], longitudinal studies would be more informative about the genetic and environmental influences behind the long-term associations between LTPA and academic skills. This is because the twin modeling results are always age- and time-specific, as well as sensitive to changes in the overall and environmental variances. For example, we have shown in our previous study that an emotionally warm, supportive, and encouraging family environment in childhood can enhance children's genetic potential for voluntary physical activity even years after the influence of the home environment in childhood[30].

Major strengths of our study are the population-based sample and its large size and relatively equal sex representation. Due to the very high participation rate, various selection biases are also unlikely in our study. Thus, the generalizability of our study findings is good but limited to individuals at age 11–12 years. A further strength is that we were able to use two different measures to assess genetic influences affecting physical activity behavior: twin modeling and PGSs.

Despite some limitations, our study certainly adds to the understanding of the association between LTPA and academic performance. The most obvious finding to emerge from this study is that the roots of the associations between LTPA and academic skills related to writing and reading may be due to common genetic influences rather than causality as previously speculated. However, it is important to be cautious interpreting our results because our sample size may not have been large enough for the bivariate twin modeling analyses. Thus, this study should be repeated using larger twin or family samples – this may enable a more reliable assessment of potential overlapping shared environmental influences between LTPA and academic skills.

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AUTHOR CONTRIBUTIONS

R.J.R. and J.K. designed and contributed to the data collection of the FinnTwin12 study. S.A., U.M.K., J.K., and K.S. designed the present study. S.A., T.P. and K.S. conducted the statistical analyses. S.A. drafted the manuscript and T.P., R.J.R., J.K., U.M.K. and K.S. critically revised the manuscript. All authors approved the final manuscript. The authors declare no conflict of interest.

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Table 1 Trait correlations (r_{trait}) as well as the correlations between additive genetic (r_A), shared environmental (r_C) and unique environmental (r_E) influences for LTPA and academic skills with 95% confidence intervals at age 12.

			Trait correlation	**Additive genetic correlation**		**Shared environmental factors**		**Unique environmental factors**	
Trait 1	Trait 2	Model	r_{trait} (95% CI)	r_A (95% CI)	% Explained of r_{trait}	r_C (95% CI)	% Explained of r_{trait}	r_E (95% CI)	% Explained of r_{trait}
Spelling	LTPA	Sexes combined	0.05 (0.01 to 0.09)	0.08 (-0.06 to -0.22)	80%	0.03 (-0.35 to 0.40)	11%	0.02 (-0.05 to 0.09)	9%
Essay writing	LTPA	Sexes combined	0.06 (0.02 to 0.09)	0.14 (0.00 to 0.28)	*	-0.13 (-0.66 to 0.25)	*	0.03 (-0.05 to 0.10)	11%
Reading aloud	LTPA	Sexes combined	0.05 (0.01 to 0.09)	0.11 (-0.03 to 0.25)	*	-0.06 (-0.41 to 0.24)	*	0.05 (-0.02 to 0.12)	22%
Reading comprehension	LTPA	Sexes combined	0.05 (0.01 to 0.09)	0.01 (-0.13 to 0.14)	7%	0.16 (-0.11 to 0.44)	78%	0.03 (-0.04 to 0.11)	14%
Mathematics	LTPA	Sexes combined	0.08 (0.04 to 0.12)	0.11 (-0.04 to 0.26)	74%	0.06 (-0.37 to 0.46)	14%	0.04 (-0.03 to 0.11)	12%

CI=confidence intervals, LTPA=leisure-time physical activity, *= cannot be calculated reliably

Table 2 Associations between genetic susceptibility to physical activity behavior (presented as polygenic scores) and academic skills when sex and the first 10 principal components are taken into account.

	Genetic susceptibility to physical activity behavior											
	Accelerometer-measured physical activity						**Questionnaire-based physical activity**					
	$PGS_{MEASURED\ WALKING}$		$PGS_{MEASURED\ MODERATE}$		$PGS_{MEASURED\ TOTAL}$		$PGS_{WALKING}$		$PGS_{MODERATE}$		$PGS_{VIGOROUS}$	
	B-coeff.	p-value	B-coeff.	p-value	B-coeff.	p-value	B-coeff.	p-value	B-coeff.	p-value	B-coeff.	p-value
Spelling	0.05	0.13	0.04	0.24	0.04	0.26	0.004	0.91	-0.01	0.76	-0.05	0.15
Essay writing	0.05	0.15	0.04	0.24	0.02	0.65	-0.04	0.31	-0.05	0.58	-0.06	0.15
Reading aloud	0.03	0.32	0.03	0.37	0.03	0.44	-0.01	0.71	-0.004	0.92	-0.04	0.27
Reading comprehension	0.04	0.19	0.01	0.75	0.02	0.60	-0.01	0.67	-0.03	0.34	-0.06	0.09
Mathematics	0.02	0.48	0.02	0.61	0.03	0.32	-0.001	0.97	0.006	0.86	-0.03	0.32

PGS=polygenic scores