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Combined Iron Deficiency and Low Aerobic Fitness Doubly Burden Academic Performance among Women Attending University

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Abstract

Background: Academic success is a key determinant of future prospects for students. Cognitive functioning has been related to nutritional and physical factors. Here, we focus on iron status and aerobic fitness in young-adult female students given the high rate of iron deficiency and declines in fitness reported in this population.

Objectives: We sought to explore the combined effects of iron status and fitness on academic success and to determine whether these associations are mediated by cognitive performance.

Methods: Women (n = 105) aged 18–35 y were recruited for this cross-sectional study. Data were obtained for iron biomarkers, peak oxygen uptake (VO_{2peak}), grade point average (GPA), performance on computerized attention and memory tasks, and motivation and parental occupation. We compared the GPA of groups 1) with low compared with normal iron status, 2) among different fitness levels, and 3) by using a combined iron status and fitness designation. Mediation analysis was applied to determine whether iron status and VO_{2peak} influence GPA through attentional and mnemonic function.

Results: After controlling for age, parental occupation, and motivation, GPA was higher in women with normal compared with low ferritin (3.66 ± 0.06 compared with 3.39 ± 0.06; P = 0.01). In analyses of combined effects of iron status and fitness, GPA was higher in women with normal ferritin and higher fitness (3.70 ± 0.08) than in those with 1) low ferritin and lower fitness (3.36 ± 0.08; P = 0.02) and 2) low ferritin and higher fitness (3.44 ± 0.09; P = 0.04). Path analysis revealed that working memory mediated the association between VO_{2peak} and GPA.

Conclusions: Low iron stores and low aerobic fitness may prevent female college students from achieving their full academic potential. Investigators should explore whether integrated lifestyle interventions targeting nutritional status and fitness can benefit cognitive function, academic success, and postgraduate prospects.

Keywords: aerobic fitness, iron deficiency, women, young adult, grade point average

Abbreviations: ACSM, American College of Sports Medicine; AGP, a1-acid glycoprotein; GPA, grade point average; HF, higher-fitness; ID, iron-deficient; IS, iron-sufficient; LF, lower-fitness; RDW, red blood cell distribution width; RPE, rating of perceived exertion; TBI, total body iron; TSAT, transferrin saturation; VO_{2peak}, peak oxygen uptake.

Introduction

Academic success, most commonly judged in college settings by grade point average (GPA), is a key determinant of future prospects (1). Whether seeking employment, a fellowship, or admittance to a postgraduate academic program, a higher GPA may facilitate more and better opportunities (2).

Multiple genetic and environmental factors are likely to influence how well one performs in the classroom (3). Two modifiable determinants of academic success include nutritional status and physical fitness, thereby making them potential targets for lifestyle interventions. Within the nutrition realm, iron has been identified as a micronutrient associated with cognitive function and has well-described roles in neurotransmitter kinetics, myelination, and brain energy metabolism (4, 5). Compared with iron-sufficient (IS) individuals, iron-deficient (ID) individuals exhibit worse executive function (6, 7) and show electrophysiologic abnormalities [prolonged latency to N2 and smaller P300 amplitude (8, 9)], consistent with animal models of iron depletion (10).

Physical fitness, and particularly aerobic fitness, has also been associated with brain structure and function, cognition, and school performance in children (11); cognitive performance in young adults (12); and executive function in the elderly (13).

Given the public health issues of overweight and obesity among children and young adults, it is crucial to understand the ramifications of low aerobic fitness.

Despite progress to date examining how iron status and aerobic fitness relate to neuropsychological outcomes, we are not aware of studies published in peer-reviewed journals that relate these factors to GPA. Given that GPA is a highly translatable measure, we felt that it was important to fill this gap.

Our aims were to assess the independent and combined effects of iron status and aerobic fitness [peak oxygen uptake (VO_{2peak})] on GPA among healthy college-aged women. We hypothesized that both better iron status and higher VO_{2peak} would be associated with higher GPA and that college-aged women with optimal iron status and high VO_{2peak} would exhibit the highest GPA. A secondary goal was to assess whether cognitive performance, as determined by using computerized tasks of attention and working memory, mediated the associations between iron status, fitness, and GPA. We hypothesized that cognitive performance would serve as a mediator through which these lifestyle factors influence academic standing.

Methods

Participants and study design. This cross-sectional study was conducted on the University Park campus of The Pennsylvania State University. The original study aim was to examine interrelations between iron status, fitness, and cognition; and full methodologic details are available elsewhere (7, 12). Although the 2 previously published studies were limited to examinations of how iron status and fitness are related to performance on computerized cognitive tasks, the current study builds in academic performance to this network of associations as a highly meaningful outcome. The study was powered to detect a difference in attention and memory performance between ID and IS groups by using our previously collected data from a field study in India where we used computerized cognitive tasks similar to those in the current study. We also performed a power calculation to determine the sample size needed to detect a difference in cognitive performance between fitness groups on the basis of a previous report in college-aged women (14), which resulted in fewer subjects necessary to observe an effect than in the iron status power calculation. Therefore, we are confident that the sample size was sufficient to detect group differences for both iron status and fitness group comparisons. Anthropometric, questionnaire, hematologic, and fitness measures occurred within a 2-wk window for each woman. Inclusion criteria were as follows: 18–35 y of age, nonpregnant and nonlactating, BMI (in kg/m^2) between 18 and 30, nonanemic as defined by hemoglobin concentrations ≥12.0 g/dL, no chronic illness or disease, no cardiovascular conditions or physical injury, proficient in the English language, and normal or corrected-to-normal vision. Approval was obtained from the Institutional Review Board of The Pennsylvania State University, and all study procedures were in accordance with the Declaration of Helsinki. All of the study participants provided written consent before any specimen collection or testing.

Hematologic testing. A trained nurse at the campus Clinical Research Center collected a blood sample from each woman with the use of antecubital venipuncture. A complete blood count was conducted on whole blood to determine hemoglobin and red blood cell distribution width (RDW; Coulter AcT diff2; Beckman-Coulter). If hemoglobin was <12 g/dL, the participant was excluded from the study and referred to her physician for follow-up. Plasma was used for determination of plasma iron and total iron binding capacity (TIBC), as described elsewhere (15); ferritin and transferrin receptor (TfR; Ramco Laboratories, Inc.); and a1-acid glycoprotein (AGP; Kent Laboratories) to account for inflammation given that ferritin is an acute-phase protein that is falsely elevated during inflammation. Transferrin saturation (TSAT) was calculated by using Fe/TIBC × 100, and total body iron (TBI) was estimated according to Cook et al. (16) with the use of the following equation:

$$\frac{-\log(\text{ferritin/TfR}) - 2.8229}{0.1207} \quad (1)$$

Fitness testing. VO_{2peak} was measured during a progressive treadmill test modified from Åstrand and Saltin (17). The women self-selected a comfortable walking, jogging, or running speed at 0% grade that could be sustained for 10 min. After a 2-min warm-up, grade was increased every 2 min for the first 6 min, followed by a 1% grade increase every minute until volitional exhaustion. Oxygen consumption was measured by using a SensorMedics Vmax metabolic cart in the Women's Health and Exercise Laboratory on campus, and ratings of perceived exertion (RPEs) were used as a subjective measure of exercise intensity (18). Although VO_{2peak} is considered the gold standard of cardiorespiratory fitness testing, it is required that each participant attains their full aerobic capacity during the test. As such, exercise test data were reviewed by 2 investigators independently to ascertain that participants met standard criteria for the achievement of VO_{2peak}. Data evaluated included oxygen consumption, heart rate, respiratory exchange ratio, which is defined as carbon dioxide production relative to oxygen consumption, and RPE (18). In agreement with guidelines of the American College of Sports Medicine (ACSM) as well as the literature (19, 20), VO_{2peak} was considered to be achieved if participants met 3 of the following 4 criteria: *1*) a plateau in oxygen consumption despite an increase in workload; *2*) attainment of 90% of age-predicted maximal heart rate, which was calculated as 220 – age; *3*) a respiratory exchange ratio ≥1.1, which is reflective of predominantly anaerobic energy provision; and *4*) attainment of an RPE ≥ 18, which is reflective of a subjective rating of exercise intensity of at least "very hard" (18).

Cognitive testing. Full details of the computerized cognitive testing have been described elsewhere (7). The Psychology Experiment Building Language platform was used to administer tasks of executive function on laptop computers in a quiet room at the Clinical Research Center on campus (21). Each 50-min testing session was monitored by trained research staff, and environmental distractions were minimized. Due to meeting the criteria for the mediation analysis, the 2 tasks included in the current analyses were the attentional network task, a modified flanker task designed to assess 3 distinct components of attention (22), and Sternberg's Working Memory Search task, which requires participants to memorize sets of letters (either 3, 5, or 8 consonants) and then decide whether subsequent probe letters were either present or absent from the memorized set (23). Before the cognitive test, a questionnaire was administered to collect information on GPA, age, socioeconomic status (24), and motivation (25).

Statistical methods. We compared groups with the following: *1*) low and normal iron stores (ferritin ≤12 compared with ≥20 μg/L), excluding women with marginal iron stores (ferritin between 13 and 19 μg/L); *2*) high or normal cellular iron demand (TfR ≥8.3 compared with <8.3 mg/L); *3*) negative or positive TBI; *4*) low or normal TSAT (≤16% compared with >16%); *5*) elevated or normal variability in RDW (≥15% compared with <15%); and *6*) 0, 1, or ≥2 abnormal iron biomarkers from ferritin, TfR, TSAT, and RDW.

For fitness group comparisons, we classified women by using the ACSM_s VO_{2peak} reference values for women aged 20–29 y (26). Due to the sample size in some of the 6 ACSM groupings, we collapsed groups into the lowest 2 ("very poor" and "poor"), middle 2 ("fair" and "good"), and highest 2 ("excellent" and "superior") groups.

The final comparison was based on groups defined according to both iron status and fitness, with the use of the following definitions: ID = ferritin ≤12 μg/L, IS = ferritin ≥20 μg/L, lower-fitness (LF) = VO_{2peak} ≤44.3 mL · kg^{-1} · min^{-1}, and higher-fitness (HF) = VO_{2peak} > 44.3 mL · kg^{-1} · min^{-1}. This strategy resulted in 4 groups: ID + LF, ID +HF, IS + LF, and IS + HF. The sample median split (median = 44.3 mL · kg^{-1} · min^{-1}) for fitness classification allowed us to preserve sample size and retain a spread in fitness, with mean VO_{2peak} values of 38.1 and 51.6 mL · kg^{-1} · min^{-1} in the LF and HF groups, respectively.

Group differences were assessed first by using ANOVA, then using ANCOVA with age, socioeconomic status, motivation, VO_{2peak} (only in the iron status group comparisons), and ferritin (only in the aerobic fitness group comparisons) as covariates given that these factors may affect cognitive performance. Post hoc Tukey tests were used to assess differences between ≥3 groups. Participants with missing data (n = 22) were not included in the analyses.

A secondary exploratory aim was to link fitness and cognitive and academic performance together in a single model. Mediation analysis was used to explore whether associations between aerobic fitness and academic performance were mediated by attention and working memory, represented by performance on computerized cognitive tasks. We previously reported on independent associations between aerobic fitness or iron status and performance on computerized cognitive tasks of executive function (7, 12). A multiple mediator model was constructed by using the SAS INDIRECT macro (27), which uses a traditional Baron and Kenny (28) approach and generates bias-corrected 95% CIs for the indirect effects with the use of bootstrapping procedures. Age, socioeconomic status, motivation, and iron status were included as covariates. SAS software version 9.4 (SAS Institute) was used, and findings were considered significant when $P < 0.05$.

Results

Sample description. Of the 127 women in the parent study, 105 women had complete data for the hematologic, fitness, and academic performance variables and thus were eligible for the current analyses. The college-aged women were predominantly white and were a mix of undergraduate and graduate students, with 65% aged 18–22 y. The median GPA was 3.68, corresponding to the cutoff used in many undergraduate courses to earn a grade of "A–," indicating that, on average, participants were strong students. The mean VO_{2peak} of 44.8 mL · kg^{-1} · min^{-1} decreased to between the 80th and 85th ACSM aerobic fitness percentiles for women aged 20–29 y (26), suggesting that aerobic fitness was high, on average, and only 25% of women were overweight. Iron stores were low (ferritin ≤12 μg/L) in 46% of this subsample, and 24% of women had negative body iron stores. We oversampled for low iron status, with the goal of half of the women having low iron stores, defined by ferritin concentrations ≤12 μg/L; thus, the prevalence of iron deficiency in our sample is not indicative of the population prevalence. The rate of inflammation was low, with only 3 women having elevated AGP; thus, ferritin values were left unadjusted (Table 1).

Table 1. Demographic, fitness, and hematologic characteristics of women in a university setting[1]

Demographic characteristics	Values
Age, y	22.4 ± 3.4
Grade point average	3.68 ± 0.04
BMI, kg/m^2	23.0 ± 2.8
Normal weight (18.5–24.9), %	75
Overweight (25.0–29.9), %	25
Socioeconomic status[2]	67.8 ± 19.9
Motivation[3]	3.6 ± 0.6
Fitness characteristics	
VO_{2peak}, mL · kg^{-1} · min^{-1}	44.8 ± 8.2
ACSM fitness classification,[4] %	
Very poor to poor	14
Fair to good	32
Excellent to superior	53
Hematologic characteristics	
Hemoglobin, g/dL	13.1 ± 0.8
Red blood cell distribution width, %	13.4 ± 1.1
≥15%, %	10
Ferritin, μg/L	19.0 ± 2.2
≤12 μg/L, %	46
≥20 μg/L, %	54
Transferrin receptor, mg/L	5.4 ± 2.0
≥8.3 mg/L, %	8
Estimated total body iron,[5] mg/kg	3.1 ± 3.7
<0 mg/kg, %	24
Transferrin saturation, %	26.4 ± 12.4
≤16%, %	19
α1-Acid glycoprotein, g/L	54.6 ± 22.1
≥1.0 g/L, %	3
Multiple iron biomarker classification,[6] %	
0 abnormal iron indicators	48
1 abnormal iron indicator	31
≥2 abnormal iron indicators	21

1. n = 105, which varies slightly depending on the variable. Unless otherwise indicated, values are means ± SDs except for grade point average and ferritin, which are presented as medians± SEs. ACSM, American College of Sports Medicine; VO_{2peak}, peak oxygen uptake.
2. Determined by using the Nam-Powers-Boyd scale (24).
3. Determined by using Lounsbury and Gibson's measure (25).
4. Fitness categories are based ACSM VO_{2peak} reference values for women aged 20–29 y (26).
5. Calculated by using Cook's equation (16).
6. The definition of multiple iron biomarker is based on abnormal markers from ferritin ≤12 μg/L, transferrin receptor ≥8.3 mg/L, transferrin saturation ≤16%, and red blood cell distribution width ≥15%.

Iron status group comparisons. ID women performed worse academically than did IS women when defining iron status according to ferritin concentrations (F = 8.5, P < 0.01), TBI (F = 5.2, P = 0.03), and RDW (F = 5.4, P = 0.02) (Figure 1). After covariates were added to the models, the difference between TBI groups lost significance (P = 0.14) and that between RDW groups trended toward significance (P = 0.09). TfR and TSAT group comparisons were nonsignificant. After applying the multiple biomarker definition, women with either 1 abnormal iron biomarker (P = 0.03) or ≥2 abnormal iron biomarkers (P < 0.01) had a lower GPA than did women with no iron biomarker abnormalities. After the addition of covariates, the difference between women with 0 and ≥2 abnormal indicators became a trend (P = 0.08) and that between women with 0 and 1 abnormal indicator became nonsignificant (P = 0.44).

Aerobic fitness group comparisons. With the use of the ACSM fitness classifications for women aged 20–29 y (26), 15 (14%), 34 (32%), and 56 (53%) women were classified as having "very poor to poor," "fair to good," and "excellent to superior" fitness, respectively, with respective group mean VO_{2peak} values of 31.9, 40.4, and 51.0 mL · kg^{-1} · min^{-1} (Figure 1). Higher GPA was observed in those with "excellent to superior" fitness than in those with "very poor to poor" fitness (P = 0.05), which held after covariate addition (P = 0.05). Those with "fair to good" fitness showed a trend for higher GPA than those with "very poor to poor" fitness in the model with covariates (P = 0.08).

Combined effect of iron status and fitness. Given that iron status and fitness were independently related to academic performance, we next examined whether these factors additively benefited GPA by using a 4-group comparison. The use of the iron storage definition (ferritin ≤12 μL indicating absence of iron stores and ferritin ≥20 μL indicating presence of iron stores) and a sample median VO_{2peak} split resulted in 24 (24%), 19 (19%), 31

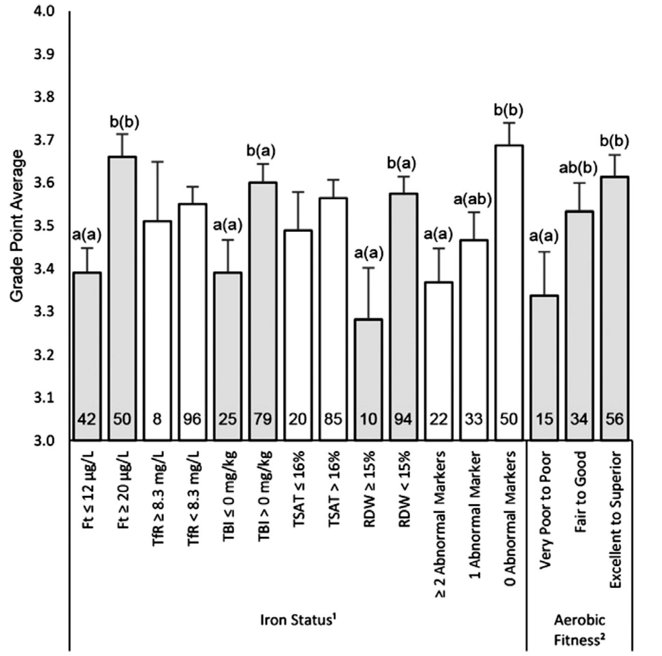

Figure 1. Grade point average comparisons for university-aged women grouped according to either iron status or fitness separately, before and after controlling for covariates. Values are group medians ± SEs. The number of women per group is shown in the base of each bar. Within a given comparison, groups without a common letter differ, P < 0.05 (with differences after controlling for covariates shown in parentheses). For 3 and 4 group comparisons, significance from a post hoc Tukey's test is reported. Covariates included in all models were age, socioeconomic status, work drive, and VO_{2peak}.

1. Multiple biomarker definition is based on the number of abnormal markers from Ft ≤12 μg/L, TfR ≥8.3 mg/L, TSAT ≤16%, and RDW ≥15%.
2. Fitness categories are based on American College of Sports Medicine VO_{2peak} reference values for women aged 20–29 y (26). Ft, ferritin; RDW, red blood cell distribution width; TBI, estimated total body iron with the use of Cook's equation (16); TfR, transferrin receptor; TSAT, transferrin saturation; VO_{2peak}, peak oxygen uptake.

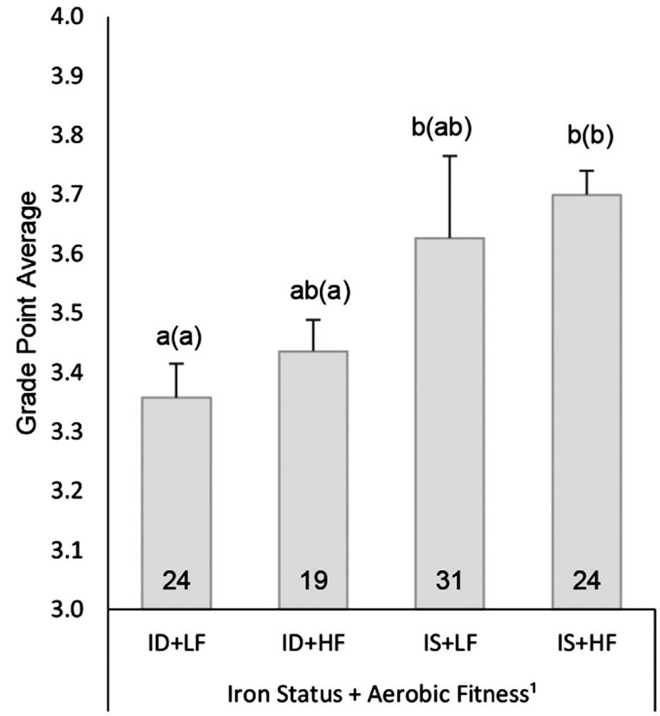

Figure 2. Grade point average comparison in university-aged women grouped according to both iron status and fitness combined, before and after controlling for covariates. Values are group medians ± SEs. The number of women per group is shown in the base of each bar. Groups without a common letter differ, P < 0.05 (with differences after controlling for covariates shown in parentheses). Significance from a post hoc Tukey's test is reported. Covariates included in all models were age, socioeconomic status, and work drive.

1. ID = ferritin ≤12 μg/L; IS = ferritin ≥20 μg/L; LF = VO_{2peak} less than the sample median LF group mean of 38.1 mL · kg^{-1} · min^{-1}; HF = VO_{2peak} more than the sample median HF group mean of 51.6 mL · kg^{-1} · min^{-1}. HF, higher-fitness; ID, iron-deficient; IS, iron-sufficient; LF, lower-fitness; VO_{2peak}, peak oxygen uptake.

(32%), and 24 (24%) women in the ID + LF, ID + HF, IS + LF, and IS + HF groups, respectively (Figure 2). A stepwise pattern was observed whereby those in the ID + LF group had the lowest GPA and those in the IS + HF group had the highest GPA, with intermediate GPA in the ID + HF and IS + LF groups. Post hoc analysis revealed a significant difference between the ID + LF and IS + HF groups (P = 0.01) and a trend between the ID + LF and IS + LF groups (P = 0.07). After covariate addition, a difference emerged between the ID + HF and IS + HF groups (P = 0.04), and the findings mentioned above remained significant.

Mediating effect of cognitive performance. The criteria to test for mediation did not hold when examining the interrelations between iron status, cognitive performance, and GPA. However, for the interrelations between aerobic fitness, cognitive performance [for 2 cognitive outcomes: accuracy on tasks of sustained attention (29) and working memory (23)], and GPA, the mediation criteria were met. A significant mediating effect of cognitive performance on the association between VO_{2peak} and GPA was found, with a reduction in the direct effect after the mediators were added to the model, which controlled for age, socioeconomic status, motivation, and iron status (Figure 3). The coefficient for the direct effect of VO_{2peak} on GPA (c = 0.014, P = 0.01) lost significance after considering the effects of cognitive performance (c≤ = 0.008, P = 0.14). The bootstrapped unstandardized indirect effect of working memory performance was 0.005 (95% bias-corrected CI: 0.000, 0.011), which indicated significance.

Discussion

Our study has 4 main findings: *1*) iron status was related to GPA, such that better iron status was associated with higher GPA; *2*) a positive association between aerobic fitness and GPA was found when defining fitness according to current ACSM guidelines; *3*) women with both good iron status and high aerobic fitness had the highest GPA and women with both poor iron status and low aerobic fitness had the lowest GPA; and *4*) performance on a task of working memory mediated the association between aerobic fitness and GPA. As such, we conclude that nutritional status and aerobic fitness are modifiable factors linked to academic success in college-aged women.

We are not aware of any work that relates iron status to GPA in college-aged women, but iron status has been related to school performance in children. ID nonanemic children (6–16 y of age) had a >2-fold risk of scoring below average in mathematics compared with IS children after controlling for age, sex, race, poverty status, caretaker education, and lead status (30). The ability of iron supplementation to improve academic achievement in children remains equivocal. In ID anemic Indonesian children supplemented with iron for 3 mo, greater

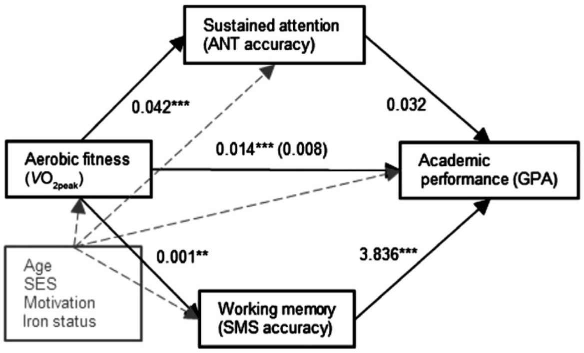

Figure 3. Mediating effects of sustained attention and working memory performance on the association between aerobic fitness and academic performance in university-aged women, while controlling for covariates. Unstandardized path coefficients are shown. **$P < 0.05$, ***$P < 0.01$. The path coefficient for the direct effect in the full model is shown in parentheses. Mediators are accuracy (proportion of correct responses) on the ANT and SMS task. SES was assessed by using the Nam-Powers-Boyd index (24), and motivation was assessed by using Lounsbury and Gibson's work drive measure (25). ANT, attentional network task; GPA, grade point average; SES, socioeconomic status; SMS, Sternberg Memory Search; VO_{2peak}, peak oxygen uptake.

improvements in iron status were associated with greater improvements in school achievement test scores (31). However, other work in Thai children suggested no benefit of iron supplementation on academic outcomes, which may be due to high baseline iron status in 1 study (32) and an improvement in iron status in the placebo group in the other study (33). In college students, we previously showed that women whose iron status responded to a 16-wk iron intervention experienced greater improvements in attention, learning, and memory domains than did nonresponders (4). Thus, it is plausible that iron supplementation among college-aged women may confer an academic advantage as well.

A few studies related physical fitness to academic success in young-adult students. One pilot investigation found positive associations between fitness scores—maximum number of pushups and pullups as well as running, biking, or swimming times— and GPA in a cohort of military medical students (34). Another study found no correlation between fitness and GPA in health science graduate students in Texas, possibly due to the limited GPA variability and the use of a questionnaire to assess fitness (35). A different group reported that normal-weight students had higher GPAs than did overweight students (36). In our sample, although GPA was marginally higher in normal-weight women (n = 72; GPA = 3.56) than in overweight women (n = 25; GPA = 3.48), the difference did not reach significance. This finding is not surprising given that aerobic fitness encompasses more than just body mass.

We found an additive benefit of good iron status and high aerobic fitness on GPA. The difference in mean GPA between the ID + LF and IS + HF groups was 0.34, which is equivalent to an SD of 0.77 considering the GPA distribution of the total sample. This difference, for example, would distinguish an "A" student with a GPA of 3.70 from a "B" student with a GPA of 3.36, which is a meaningful difference. This finding of additive benefit also suggests that interventions should target both diet and lifestyle for maximal benefit.

There are many potential paths through which aerobic fitness may act to benefit GPA, but a plausible one is that which we have described in our mediation analysis, namely that aerobic fitness might enable an individual to achieve greater academic success through improved cognitive function. The literature linking acute exercise and brain function strongly supports this model, with convincing data in both animals and humans that show that exercise promotes neural plasticity via angiogenic, neurogenic, and apoptotic pathways mediated by brain-derived neurotrophic factor, vascular endothelial growth factor, and insulin-like growth factor I, all of which are released after physical activity (37–39). The link between chronic exercise habits, as would be reflected in VO_{2peak}, and brain plasticity is more ambiguous, as discussed by Swain et al. (40). Nonetheless, we and others (41, 42) detected associations between VO_{2peak} and behavior in young adults, mostly in terms of executive functions. The mediation approach is strengthened by the fact that we controlled for age, socioeconomic status, motivation, and iron status, but it is likely that factors in addition to working memory, such as sleep habits, status of other nutrients that may affect brain function, and so on, are also involved. From a public health perspective, however, the association between fitness and GPA must be of concern independent of whether the precise mechanisms are fully understood.

Future investigation could be refined by collecting information on academic major or standing. Obtaining a high GPA may be more difficult in some majors than in others, and a given GPA may not be equivalent at the undergraduate and graduate levels. Due to privacy issues associated with obtaining official academic records, GPA in our study was self-reported. However, high self-reported grade validity in college students has been shown. In a meta-analysis that included 12,089 college students, Kuncel et al. (43) found high agreement (r = 0.90; 95% CI: 0.82, 0.98) between self-reported grades and those obtained from academic records. They also found overreporting to be more problematic in students with lower grades, which, if true for our study, would suggest even larger GPA group differences than were observed. Future work should also examine the association between iron status and fitness and GPA in men, minority and socially disadvantaged groups, students with poorer grades, and sedentary populations. In addition, longitudinal designs are important for establishing temporality; given our cross-sectional design, we cannot rule out the possibility of reverse causality. For example, one could speculate that a low GPA may result in increased sedentary behavior associated with more time spent studying to pull up one's grades.

We conclude that combined iron deficiency and low aerobic fitness—importantly, both modifiable factors—may doubly burden academic success in young-adult women. Public health interventions that use multiple strategies and actions at multiple levels are most effective (44). This is the first study, to our knowledge, that examines both iron status and aerobic fitness in relation to academic success in students attending university. Our sample consisted of women with a range of fitness levels (VO_{2peak} range: 24.2–66.3 $mL \cdot kg^{-1} \cdot min^{-1}$, spanning the 1st–99th percentiles of aerobic fitness for women aged 20–29 y according to the ACSM) and academic success (GPA range: 2.0–4.0). Several covariates that may influence iron status, aerobic fitness, and GPA were controlled for. Furthermore, we found no association between aerobic fitness and iron status (r = –0.03, P = 0.74), which may confound the associations we were interested in. We assessed aerobic fitness by using the gold-standard method, measured multiple iron biomarkers for a comprehensive iron status assessment, and performed computerized tasks that specifically target attentional and mnemonic functions. Our findings warrant further exploration of modifiable determinants of academic success in college populations and provide support for multipronged interventions targeting both nutrition and physical fitness.

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