Trends in Neuroscience and Education 23 (2021) 100154

Contents lists available at ScienceDirect

Trends in Neuroscience and Education

journal homepage: www.elsevier.com/locate/tine

Research paper

Aerobic fitness relates to superior exact and approximate arithmetic processing in college-aged adults

Amanda L. McGowan *, Madison C. Chandler, Matthew B. Pontifex

Department of Kinesiology Michigan State University, 308 W. Circle Drive, 38 IM Sports Circle, East Lansing, MI, United States, 48823

ARTICLE INFO

Keywords:
Cardiorespiratory fitness
Arithmetic strategy
Health numeracy
Young adults
Mathematics achievement

ABSTRACT

Background: Aerobic fitness relates to superior math achievement, but the underlying reasons remain unclear. This study tested how more efficient processing (efficiency hypothesis) or enhanced allocation of cognitive resources (resources hypothesis) underly fitness-related differences in arithmetic cognition in a sample of 138 college-aged adults.

Method: Participants completed an arithmetic task while pupillary measures were recorded prior to an aerobic fitness test.

Results: Higher aerobic fitness was associated with shorter reaction time for all problems and greater pupillary reactivity for problems requiring approximate and exact arithmetic.

Conclusions: Superior aerobic fitness relates to greater cognitive resources available to execute exact and approximate arithmetic faster. Fitness-related differences in math achievement may be driven by the cognitive resources underlying arithmetic strategy. These differences may extend beyond educational achievement and affect the motivation to engage in health behaviors based on quantitative information. Thus, improving cardiovascular fitness has the potential to also ameliorate health numeracy.

1. Introduction

The health-related attribute of aerobic fitness has garnered substantial contemporary attention for its influence on cognitive function and brain health across the lifespan [1,2]. Indeed, higher aerobic fitness is related to greater efficiency of neural networks underlying aspects of cognitive control, attention, and memory [3–11]. Moreover, greater physical activity participation—leading to higher aerobic fitness—is associated with superior academic achievement during childhood [12–14], adolescence [15–18], and the college years [19,20]. In particular, these fitness-related differences are most prominent for mathematics [12,13,21–27]. Two potential hypotheses may explain these fitness-related differences in mathematics. The first, known as the efficiency hypothesis, stems from the observation that higher aerobic fitness is associated with more efficient processing speed [7,28–33] and problem-solving strategies [4,12,34–37]. Thus, this hypothesis posits that high-fit individuals exhibit superior mathematics achievement because of more efficient information-processing and arithmetic strategy selection. Alternatively, the resource hypothesis draws upon the finding that high-fit individuals exhibit enhanced allocation of resources and superior integrity of neural networks underlying information processing [30,32,33,38–41]. Thus, this hypothesis posits that high-fit individuals have more cognitive resources available and perhaps greater neural connectivity whereby they are able to solve more demanding problems, resulting in higher mathematics achievement. Beyond simple behavioral measures, one way to index these processes—and thus test these hypotheses—is via the use of pupillometry, which provides evidence of cognitive resource allocation or effort level in the context of a particular task [42]. Accordingly, the purpose of this investigation was to provide an initial assessment of the extent to which aerobic fitness is associated with behavioral and pupillometric indices of arithmetic processing to shed light on whether fitness-related differences in mathematics stem from individual differences in cognitive efficiency or cognitive resources.

Because arithmetic is an important skill for children to master, is used by adults in daily life, influences later mathematics achievement, and is an important component of health literacy [43,44], understanding the development of arithmetic proficiency on behavioral and neural levels has garnered a great deal of interest. Notably, mathematical reasoning skills can affect health through interactions with the health

* Corresponding author at: Annenberg School for Communication, University of Pennsylvania, Philadelphia, PA 19104.
E-mail address: amanda.mcgowan@asc.upenn.edu (A.L. McGowan).

https://doi.org/10.1016/j.tine.2021.100154
Received 13 November 2020; Received in revised form 20 February 2021; Accepted 10 March 2021
Available online 14 March 2021
2211-9493/

care system and exerting an influence on health behaviors, such as physical activity participation. Approximately 61% of adults in the United States are unable to perform the most rudimentary quantitative skills [45], with many adults demonstrating adequate health literacy skills in the absence of basic numeracy skills [46]. Indeed, it is not uncommon to perform basic arithmetic calculations in the context of interpreting blood glucose readings and food labels. In this context, mathematical reasoning may be particularly important for optimal health literacy, which includes the ability to complete basic calculations [46]. Variations in such quantitative skills might explain some of the disparities in health attributed to socioeconomic status, including academic achievement; however, the extent to which modifiable health factors—such as aerobic fitness—contribute to individual differences in arithmetic proficiency (an important aspect of health literacy) remains largely underspecified. Arithmetic proficiency is marked by a shift from using effortful, inefficient strategies to more automated and efficient strategies during problem-solving [47]. In particular, arithmetic performance is influenced by both strategy efficiency—the speed and accuracy at which a solution is reached—and strategy selection—the procedures used to solve problems [48]. The Adaptive Strategy Choice Model [49] of cognitive arithmetic suggests that skill development occurs as a result of enhanced adaptation to selecting alternative strategies for problem-solving. With greater arithmetic proficiency—such as in adults—individuals rely more on retrieval, which is primarily an automated process [50]. In the context of influencing engagement in health behaviors, greater aerobic fitness may lead to better processing of simple computations, which can then lead to better adherence and motivation to engage in physical activity based on quantitative information. For example, individuals higher in aerobic fitness may more easily be able to sum their daily step count and take action to adhere to federal guidelines over their lower-fit counterparts.

To assess procedural strategies underling arithmetic, a popular variant of the complex arithmetic task asks individuals to judge whether sums are greater than or less than 100 [51–53]. When adults judge a sum such as $82 + 68$ (with a sum of 150), an exact solution does not need to be calculated. Instead, individuals rely upon retrieval to make a decision if the sum is less/greater than 100 (i.e., the addends are both greater than 50, so the sum must be greater than 100), resulting in a short reaction time with a high degree of accuracy. However, when solving complex arithmetic problems, adults primarily employ two more effortful and time-consuming strategies: approximate calculation and exact calculation [51]. Exact calculation requires finding the sums of the tens and ones digits (i.e., in the case of $67 + 38$, first summating the $6 + 3$ and then summating the $7 + 8$), resulting in a slower reaction time and inferior response accuracy relative to retrieval and other procedural strategies. When employing approximate calculation by quickly estimating the solution (i.e., in the case of $42 + 73$, rounding and then summating the $40 + 70$), shorter reaction time and superior response accuracy are observed because the exact solution does not need to be determined [51]. The nature of these complex arithmetic tasks manipulates strategy such that small-split problems (i.e., sums close to 100, such as 98) require the use of exact calculation whereas large-split problems (i.e., sums farther from 100, such as 110) require approximate calculation to optimize performance. Individuals performing similarly on mathematics achievement tests exhibit a high degree of variability in executing fact-retrieval processes and across procedural arithmetic strategies [50]. Given the critical importance of relying on more proficient problem-solving strategies for supporting mathematical competence, impairments in the execution of retrieval from long-term memory and/or the use of approximate/exact calculation strategies can result in substantial downstream deficits in academic achievement and health numeracy. Accordingly, determining the influence of modifiable factors, such as fitness, affecting mathematical strategy and competence is of particular relevance in the context of potentially improving scholastic performance and improving health numeracy.

Whereas overt behavioral measures (i.e., reaction time, response accuracy) provide an index of efficiency, the assessment of task-evoked pupillary reactivity provides an objective index of cognitive resources. Indeed, task-evoked pupillary reactivity indexes the overall aggregate of cognitive resources allocated during problem-solving and corresponds to the overall functional capacity of the cognitive system [42,54–56]. Thus, task-evoked cognitive resource allocation can be indexed through pupil dynamics [57–60]. Of particular interest is the amplitude of task-evoked pupillary reactivity, which modulates as a function of task difficulty [61–64] and in response to the investment of cognitive resources during task performance [42,56]. Specifically, higher levels of pupillary reactivity are usually observed in the context of more difficult (as compared to less difficult) task conditions and can be used to indicate greater levels of cognitive resource investment. Pupillary measures are particularly useful as a way to measure strategy use in mathematics tasks because although the vast majority of studies have used participant verbal report as an index of strategy selection during problem solving, such approaches have major shortcomings. For example, individuals may change their behavior when asked to describe the procedures used for finding a solution or may be unable to describe their procedures (compromising the validity of verbal reports), and experimental procedures (i.e., task instructions) may bias the strategies participants use and report [65]. Instead, task-evoked pupillary reactivity serves as an objective, and bias-free, index of arithmetic strategy selection and cognitive resource utilization during problem-solving. In this way, findings from studies using task-evoked pupillary reactivity with other cognitive tasks [56] can be extended to suggest that pupillary reactivity would modulate by cognitive resource utilization: with the largest pupillary reactivity observed for exact calculation (as it requires the greatest amount of cognitive resources and is the most difficult), followed by approximate calculation, and then the smallest pupillary reactivity observed for retrieval (as it is most automated and thus least difficult).

At present, however, despite the critical importance of understanding the relationship between aerobic fitness and arithmetic performance, relatively little research has explored this area. In an initial investigation, Moore et al. [34] observed that higher-fit individuals reported relying on more efficient strategies (i.e., retrieval) more frequently than their lower fit counterparts during performance of a simple arithmetic verification task, and that the higher fit group exhibited superior detection of correct and incorrect solutions. These preliminary findings would appear to support the efficiency hypothesis. However, while providing initial insight testing this hypothesis, a key limitation of this investigation was the characterization of strategy use by the verbal report of the strategy used on a sample problem of the Kaufman Test of Academic and Educational Achievement 2 [66]. This verbal report was then generalized to all similar problem types encountered during the simple arithmetic verification task. Further, the nature of the simple arithmetic verification task used by Moore and colleagues [34] was such that all incorrect solutions would have required the use of exact calculation (i.e., the solutions were all within $\pm$ 1 of the correct solution, thus being too challenging to implement retrieval or approximation strategies), whereas all correct solutions would vary in strategy and be dependent upon arithmetic skill. Problematically, this differential processing of correct versus incorrect solutions in simple arithmetic verification tasks has been found to generate a Stroop-like interference effect during incorrect problems, which interferes with the ability to produce the correct solution as individuals have to engage aspects of inhibitory control to override the prepotent response [67,68]. Indeed, the arithmetic verification task used by Moore et al. [34] may have enabled higher fit children to more accurately detect correct and incorrect solutions as a function of reduced susceptibility to task interference [69–71] independent of actual differences in strategy efficiency and selection during arithmetic cognition.

Interestingly, consistent with this view, Moore et al. [34] observed that the higher-fit group exhibited a higher D-prime (d’) relative to the lower-fit group. D-prime measures an individual’s sensitivity to detect or discriminate signals: a higher d' would indicate increased sensitivity to detecting correct and incorrect answers and less reliance on guessing. Additionally, this study included a measure of event-related potentials, specifically examining the amplitude of the N400—a negative-going deflection peaking around 400 ms post-stimulus. The arithmetic N400 effect is typically elicited in response to incongruent solutions (i.e., incorrect), with larger amplitude observed for incorrect solutions, indexing the greater cognitive effort required to suppress incorrect answer representations during retrieval [72]. Moore et al. [34] found that higher-fit individuals exhibited larger N400 amplitude during incorrect problem verification relative to their lower-fit counterparts. The finding by Moore et al. [34] that higher aerobically fit individuals exhibited superior d' scores and larger N400 amplitudes relative to their lower-fit counterparts would thus appear consistent with the extant fitness and inhibitory control literature, which has observed enhanced interference control and error detection for higher-fit individuals relative to lower-aerobically-fit individuals across the lifespan [38,73]. These findings suggest that the extent to which aerobic fitness modulates the cognitive mechanics underlying mathematical reasoning remains an open question.

Taken together, further investigation is warranted to better elucidate the relationship between aerobic fitness and arithmetic processing using a complex arithmetic task to reduce potential confounds and enable the examination of potential fitness-related differences in strategy efficiency and cognitive resources. Further, complex arithmetic tasks conceptually align with the different strategies used for mental arithmetic (i.e., retrieval, approximation, and exact calculation) and are free of interference effects as individuals are making a less/greater decision rather than verifying a correct or incorrect solution. Given previous findings demonstrating that aerobic fitness-related differences in mathematics achievement [12,13,21–27] have been primarily derived from studies of school-aged children and adolescents—a population with a high degree of variability in mathematics performance—the present investigation used a sample of college-aged adults to reduce potential differences in arithmetic processing associated with mathematical competence. In addition, the drastic alterations in physical activity levels and aerobic fitness that can occur during college have the potential to negatively impact academic performance [74,75] and influence young adults' health literacy as they begin to independently interact with the healthcare system and make decisions towards engaging or not engaging in health behaviors—further underscoring the importance of studying the relationship between aerobic fitness and mathematical competence in this population. Accordingly, in a well-powered sample, the present investigation sought to characterize the extent to which aerobic fitness relates to behavioral and pupillometric indices of arithmetic processing to shed light on whether fitness-related differences in mathematics stem from individual differences in cognitive efficiency or cognitive resources. Given the considerable bodies of literature demonstrating positive associations between aerobic fitness and mathematics achievement, it was hypothesized that higher aerobic fitness would be associated with greater efficiency (i.e., shorter reaction time, greater response accuracy, smaller task-evoked pupillary activity) during arithmetic processing, thus supporting the efficiency hypothesis.

2. Method

2.1. Participants

A sample of 138 college-aged adults ($M = 18.9 \pm 1.0$ years, 74 females; 17.5% nonwhite) participated in this cross-sectional investigation (see Table 1 for participant demographic and fitness information). All participants reported being free of neurological disorders, physical disabilities, and had normal or corrected-to-normal vision. Prior to participating in the experimental session, participants completed written informed consent in accordance with the Institutional Review Board of Michigan State University and the Physical Activity Readiness Questionnaire to identify any contraindications to performing the aerobic fitness assessment [76].

Table 1
Participant demographic and fitness characteristics (mean ± SD).

Measure	All	Females	Males
N[†]	138	74	63
Age (years)	18.9 ± 1.0 [18–26]	18.9 ± 1.2 [18–26]	19.0 ± 0.8 [18–21]
Education (years)	12.9 ± 1.3 [12–18]	13.1 ± 1.6 [12–18]	12.7 ± 1.0 [12–16]
Nonwhite (%)[†]	17.5	14.9	20.6
VO_{2max} (ml/kg/min)	44.8 ± 10.2 [23.5 – 67.8]	39.5 ± 7.1 [23.5 – 56.6]	50.9 ± 8.3 [24–67.8]
VO_{2max} Percentile	51.4 ± 37.0 [3–99]	42.9 ± 35.9 [3–99]	61.7 ± 34.5 [5–97]

Note: VO_{2max} percentile based on normative values for VO_{2max} [77]. [†]$n = 1$ missing case for sex and nonwhite. Values presented in square brackets represent [minimum – maximum].

2.2. Complex arithmetic task

A modified complex arithmetic task [51] was used to assess mental arithmetic (see Fig. 1). In addition to using the same small- and large-split conditions in El Yagoubi et al. [51], a novel massive-split condition was used in the present study to include a task condition that relies upon retrieval and to serve as an effort check throughout task performance. Pilot testing of this novel task condition in a sample of 10 college-aged adults demonstrated high accuracy (≥ 95%). Following pilot testing, participants were asked to report how they solved this condition. Participants unanimously reported that they "just knew" the answer or it "popped into their head", which is consistent with the classification of retrieval in prior literature examining verbal reports of arithmetic procedural strategies in adults [65,78,79]. Sums were equally split between less than 100 and greater than 100 and equally distributed across small-split (i.e., ± 2 or 5%; 67 + 38, exact calculation), large-split (i.e., ± 10 or 15%; 42 + 73, approximate calculation), and massive-split (i.e., ± 50 or 55%; 17 + 28, retrieval) problem types (see Fig. 1). Based on previous findings in arithmetic, problems were selected using several constraints to avoid a number of confounds, (i.e., presentation order of operand, nonuse of the 0 and 5 digits, and avoiding same or repeated digits within operands) [80–82]. Following 8 practice trials, participants completed 216 addition problems divided into three blocks consisting of 73 problems each. Each block took 3 min and 20 s to complete for a total task duration of 10 min. Participants were allowed to take seated breaks in between blocks to reduce the potential confound of fatigue. Although fatigue may be of concern in any repeated measures approach, participants retained a high level of accuracy across blocks ($M \geq 83.4\% \pm 6.1$ [minimum 63 – maximum 100]. Response accuracy across blocks was positively, moderately correlated, r's ≥ 0.43, p's ≤ 0.001 suggesting fatigue unlikely affected performance. Problems consisted of two-digit numbers presented in standard form (i.e., $a + b$) for 500 ms followed by a probe 'XX' presented for 2000 ms in which participants were instructed to respond as accurately as possible whether the sum was less (left button press) or greater (right button press) than 100 on a response pad (Current Designs, Philadelphia, PA). Button-response mappings remained onscreen during the task to alleviate working memory demands.

2.3. Pupillometry

During completion of the arithmetic task, pupillometric activity was recorded at a sampling rate of 60 Hz using a table-mounted infrared eye tracker (The Eye Tribe, Copenhagen, Denmark). Gaze position was calibrated prior to task initiation using a 9-point calibration procedure to ensure quality of the recorded signal. Pupil diameter was recorded in

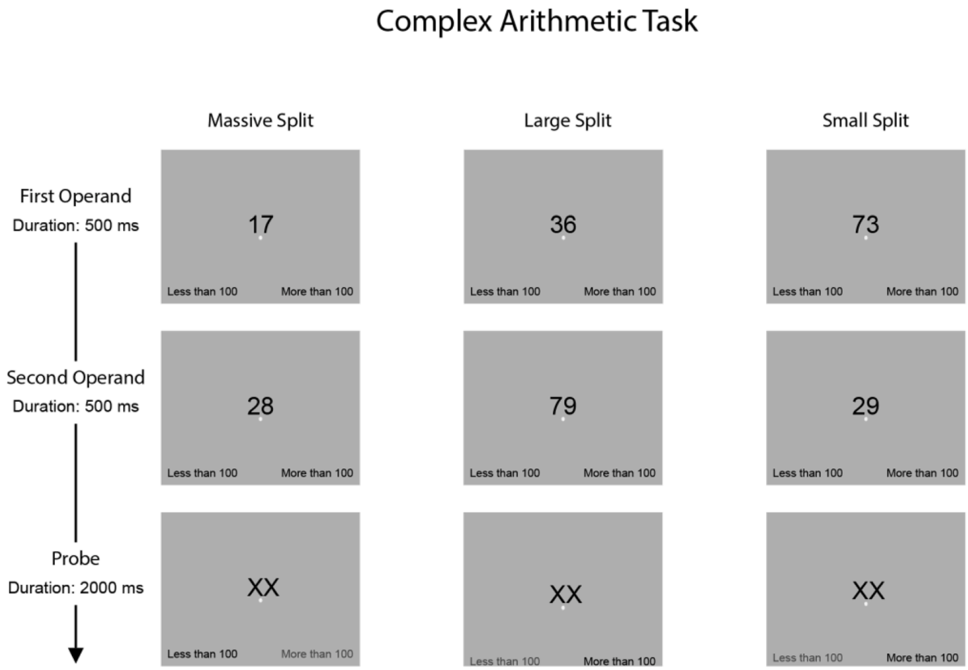

Fig. 1. Illustration of the complex arithmetic task. For reference, each split type (i.e., massive, large, small; in ascending order of difficulty) is depicted with the correct response to each problem depicted in darker font on the probe stimulus. Response mapping cues remained on the screen during task completion to alleviate working memory load.

arbitrary units and then imported into EEGLAB [83] where it was scaled to micrometers [62]. After linear interpolation of discontinuities in the data, response-locked epochs for task-evoked pupillary reactivity were filtered using a 0.02 to 4 Hz bandpass Butterworth IIR filter [62,84]. Task-evoked pupillary reactivity as an index of cognitive load was response-locked using task-evoked epochs for correct trials from 0 to 1200 ms around the response and baseline corrected to the first stimulus presentation using the −1000 to 0 ms pre-response period. Task-evoked pupillary reactivity (as an index of cognitive resources) was quantified as the mean pupil size within 0 to 1200 ms surrounding the response [61,62,85,86]. To ensure the integrity of the signal, all epochs were visually inspected blind to fitness and split size prior to computing mean waveforms across both left and right pupils (mean number of included trials [correct trials only]: small-split = 24.3 ± 5.8, large--split = 30.3 ± 6.1, massive split = 40.8 ± 15.4).

2.4. Aerobic fitness assessment

Consistent with previous investigations, participants' level of aerobic fitness was quantified measuring relative peak oxygen consumption (ml/kg/min) [see 58,80 for detailed procedures] and attainment of maximal effort was evidenced by achieving two of four criteria for reaching VO_{2max} [41]. The aerobic fitness test was conducted after the arithmetic task to avoid any exercise-induced confounds in cognition.

2.5. Statistical analysis

We tested the extent to which aerobic fitness percentile (grand mean centered) was associated with arithmetic cognition (reaction time, response accuracy, pupillary reactivity) as a function of split size in separate multilevel models. The data structure was specified as split (small, large, massive) nested within blocks (block 1, block 2, block 3) nested within 138 participants. All mixed models followed a formal model-fitting procedure for fixed and random effects, with both participant and block included as random intercepts. We included age (grand-mean centered) and sex (coded as 0 = female, 1 = male) as covariates when model convergence was possible (reaction time contained only age as a covariate). All analyses were performed using the stats [87], emmeans [88], and nlme [89] packages in R version 4.0.2 [87] with $\alpha = 0.05$. Using recently-published findings in older adolescents [90] and college-aged adults [3], we followed procedures for power analysis in multilevel models [91] and find that with a sample of 120 participants, a significant between-person association between fitness and cognitive function is observed in 90% of 1000 simulated samples. As such, the current sample of 138 should be adequately powered to detect associations between aerobic fitness and cognitive function.

3. Results

Correlations of the variables used in the multilevel analyses are provided in Table 2.

3.1. Reaction time

We ran multilevel models to examine whether fitness was associated with reaction time (see Table 3, Fig. 2A). Individuals higher in aerobic fitness responded faster than those lower in aerobic fitness ($b = -0.95$, $p < 0.001$). The interaction of Split × Fitness was unrelated to reaction time (p's ≥ 0.17). Participants responded faster to massive split problems relative to large split ($b = -120$, $p < 0.001$) and small split problems ($b = -105$, $p < 0.001$). Participants responded faster to large split trials than small split problems ($b = -105$, $p < 0.001$). Older participants responded slower than their younger counterparts ($b = 18.8$, $p = 0.01$).

3.2. Response accuracy

We ran multilevel models to examine whether fitness was associated with response accuracy (see Table 3, Fig. 2B). Fitness was unrelated to response accuracy ($b = 0.002$, $p = 0.82$). The model would not converge with the inclusion of a Split × Fitness interaction. Participants responded more accurately to massive split problems than large ($b = 7.5$, $p < 0.001$) and small split problems ($b = 24.0$, $p < 0.001$). Participants responded more accurately to large than small split problems ($b = 16.5$, $p < 0.001$). Age was unrelated to response accuracy ($b = 0.23$, $p = 0.42$).

Table 2
Correlations of demographic factors and task performance variables.

Variable	M	SD	1	2	3	4	5	6	7	8	9	10	11	12
1. Age	18.93	1.10												
2. Sex	—	—	.02											
3. Nonwhite	—	—	−0.15	.08										
4. Fitness	51.41	32.33	.19*	.29**	−0.14									
5. Small RT	602.67	194.43	.11	−0.00	−0.01	−0.08								
6. Large RT	499.56	164.09	.11	−0.18*	−0.00	−0.15	.91**							
7. Massive RT	381.45	125.53	.08	−0.20*	.06	−0.21*	.71**	.84**						
8. Small ACC	72.04	10.27	.10	.39**	−0.13	.11	.08	−0.12	−0.24**					
9. Large ACC	88.48	6.61	−0.04	.18*	−0.31**	.11	−0.03	−0.22*	−0.19*	.49**				
10. Massive ACC	95.87	2.86	.01	.08	−0.09	.03	−0.17*	−0.28**	−0.26**	.22*	.48**			
11. Small Pupil	69.19	36.13	−0.01	.09	−0.15	.13	−0.01	−0.10	−0.10	.21*	.15	−0.08		
12. Large Pupil	45.98	25.87	.06	.10	−0.10	.25**	−0.08	−0.14	−0.14	.19*	.06	−0.06	.55**	
13. Massive Pupil	26.14	26.11	−0.05	.16	−0.02	−0.01	−0.04	−0.12	−0.18*	−0.04	.00	−0.01	.33**	.32**

Note: Aerobic fitness percentile was used for the fitness variable. RT = reaction time (milliseconds). ACC = response accuracy (% correct). Pupil = Pupillary reactivity (amplitude in micrometers). * denotes $p < 0.05$. ** denotes $p < 0.001$.

Table 3
Results of the multilevel models examining associations of aerobic fitness with reaction time, response accuracy, and pupillary reactivity.

					Confidence interval			
		Effect	Estimate	Standard error	p	d	Lower	Upper
Reaction Time								
	Fixed effects							
		Intercept	380.36**	11.44	< 0.001		357.90	402.82
		Age	18.83*	7.50	0.01	0.25	4.09	33.58
		Split Large	119.51**	5.40	< 0.001	1.55	108.91	130.11
		Split Small	224.49	7.28	< 0.001	3.07	210.21	238.78
		Fitness	−0.95**	0.28	< 0.001	−0.24	210.21	238.78
		Split Large*Fitness	0.06	0.17	0.73	0.02	−1.50	−0.40
		Split Small*Fitness	0.31	0.23	0.17	0.14	−0.13	0.75
	Random effects							
		Participant	12.49				1.36	114.88
		Block	2.40				0.54	10.53
Response Accuracy								
	Fixed effects							
		Intercept	94.24**	1.12	< 0.001		92.04	96.45
		Age	0.23	0.28	0.42	0.08	−0.33	0.79
		Sex Male	3.59**	0.64	< 0.001	0.55	2.32	4.85
		Split Large	−7.52**	0.53	< 0.001	−0.99	−8.56	−6.48
		Split Small	−24.0**	0.60	< 0.001	−2.82	−25.15	−22.52
		Fitness	0.002	0.01	0.82	0.02	−0.02	0.02
	Random effects							
		Participant	1.71				0.59	4.92
		Block	1.61				0.06	46.21
Pupillary Reactivity								
	Fixed effects							
		Intercept	23.71**	2.31	< 0.001		19.17	28.24
		Age	−0.51	1.21	0.68	−0.04	−2.89	1.88
		Sex Male	4.81	2.74	0.08	0.17	−0.58	10.20
		Split Large	20.14**	2.30	< 0.001	0.62	15.63	24.65
		Split Small	43.54	2.39	< 0.001	1.82	38.85	48.22
		Fitness	−0.04	0.06	0.49	−0.05	−0.16	0.08
		Split Large*Fitness	0.21*	0.07	0.004	0.20	0.07	0.35
		Split Small*Fitness	0.17*	0.07	0.02	0.23	0.03	0.32
	Random effects							
		Participant	0.84				0.17	4.15
		Block	16.26				12.30	21.51

Note. * $p < 0.05$, ** $p < 0.001$.

Males responded more accurately than females ($b = 3.6$, $p < 0.001$).

3.3. Task-evoked pupillary reactivity

We ran multilevel models to examine whether fitness was associated with pupillary reactivity (see Table 3, Fig. 2C). Fitness was unrelated to pupillary reactivity ($b = -0.04$, $p = 0.49$). However, fitness modulated pupillary reactivity by problem difficulty such that large split ($b = 0.21$, $p = 0.004$) and small split ($b = 0.17$, $p = 0.02$) problems had larger pupillary reactivity than massive split problems. Superior fitness related to larger pupillary reactivity on large ($b = 0.17$, $p = 0.006$) and small ($b = 0.13$, $p = 0.03$) split trials. Pupillary reactivity was smaller for massive than large ($b = -20.1$, $p < 0.001$) and small ($b = -43.5$, $p < 0.001$) split problems. Pupillary reactivity was smaller for large relative to small split problems ($b = -23.4$, $p < 0.001$). Age and sex were unrelated to pupillary reactivity (p's ≥ 0.08).

4. Discussion

The aim of the present investigation was to determine the extent to

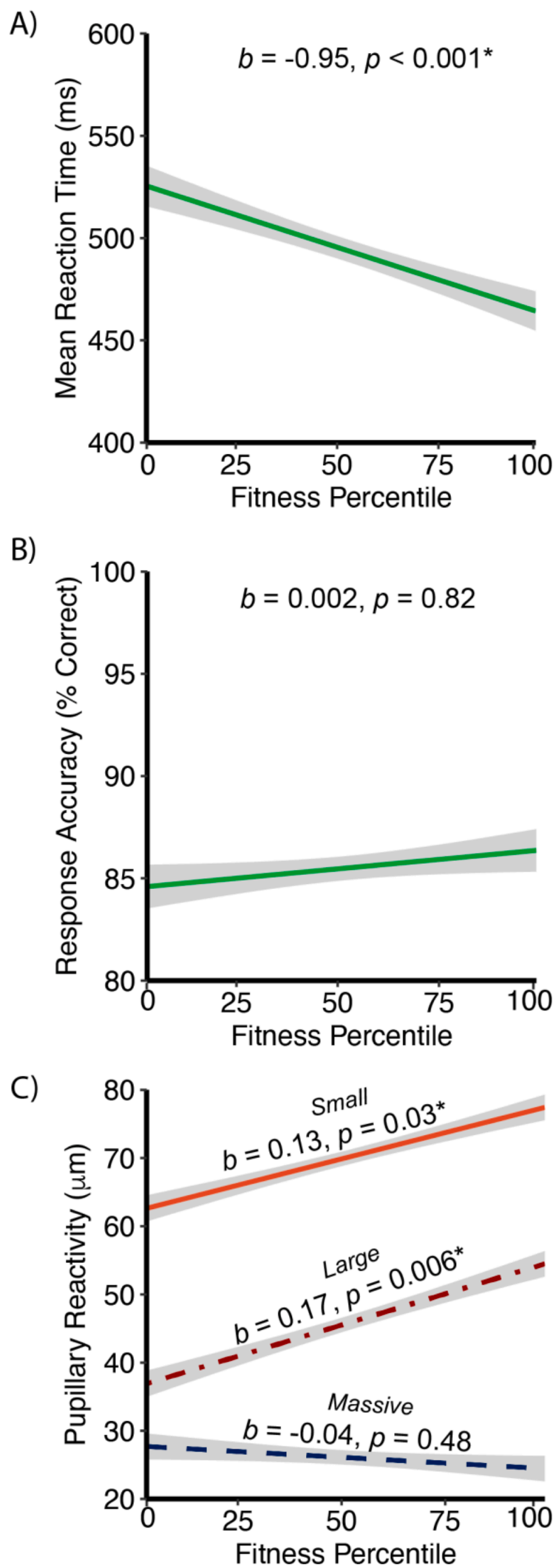

Fig. 2. Graphic representation of the multilevel models showing the association of aerobic fitness percentile with (A) mean reaction time, (B) response accuracy, and (C) pupillary reactivity. 95% confidence intervals are represented in gray. * denotes $p < 0.05$. b represents the slope of fitness.

which aerobic fitness relates to behavioral and pupillometric indices of arithmetic processing. In contrast to our a priori hypothesis that higher aerobic fitness would relate to greater efficiency (i.e., shorter reaction time, superior response accuracy, and smaller task-evoked pupillary reactivity) during arithmetic processing (supporting the efficiency hypothesis), findings revealed that higher aerobic fitness was related to shorter reaction time across all trials but unrelated to response accuracy. Furthermore, fitness related to larger pupillary reactivity for the most difficult task conditions requiring exact and approximate arithmetic. This points to support for the resource hypothesis underlying fitness-related differences in mathematics in college-aged adults such that individuals higher in aerobic fitness have greater cognitive resources to draw upon for solving more demanding problems.

Collectively, findings from the present investigation replicate the extant literature observing positive associations between aerobic fitness and mathematics achievement. Prior work by Castelli and colleagues [12] has observed that third- and fifth- grade children higher in aerobic fitness demonstrated superior scores on the mathematics component of the Illinois Standards Achievement Test, which assessed computations and problem-solving strategies. Likewise, the present findings suggest that higher aerobic fitness was related to solving the most challenging problems by drawing upon greater cognitive resources to support faster and more accurate responses. Further, although the vast majority of the present literature investigating the association of aerobic fitness with mathematics achievement has used standardized achievement tests and been conducted in school-aged children [12,13,21–27], findings from the present investigation using a complex arithmetic task observed similar associations between aerobic fitness and behavioral/pupillometric indices of arithmetic performance in college-aged young adults. Specifically, higher aerobic fitness related to shorter reaction time regardless of arithmetic strategy and greater task-evoked pupillary reactivity for executing approximate and exact arithmetic. Novel to the present investigation, fitness related to larger pupillary reactivity for small-split and large-split problems—indicating flexible modulation of cognitive resources for solving problems requiring exact and approximate calculation procedures. We replicate the robust body of literature demonstrating that aerobic fitness was associated with shorter reaction time [9,40,41,92–94]. The lack of a relationship for response accuracy is perhaps unsurprising given the use of a high-functioning population and the prolonged inter-trial interval to allow sufficient time for the phasic pupillary response, which served to reduce the variability in response accuracy and potentially mitigated the opportunity for aerobic fitness to exert an influence over this criterion of performance. The present findings provide initial evidence to suggest that aerobic fitness may positively influence mathematics achievement by benefitting the cognitive resources available to support exact and approximate calculation procedures. However, future investigations are necessary to examine the neural underpinnings subserving these arithmetic performance differences between higher fit and lower fit individuals.

The present investigation also replicated the well-established modulations in reaction time and accuracy as a function of problem difficulty in arithmetic tasks, underscoring the validity of our task [51,52]. Specifically, small-split problems requiring the most effortful and time-consuming exact calculation strategy exhibited the slowest reaction time and poorest accuracy, followed by large-split problems requiring approximate calculation, and massive-split problems requiring automated retrieval processes exhibiting the shortest reaction time and greatest accuracy. Additionally, these behavioral findings suggest that the task conditions (i.e., small-split, large-split, and massive-split) used in the complex arithmetic task elicited differing arithmetic strategies: small-split problems elicited exact calculation, large-split problems elicited approximate calculation, and massive-split problems elicited retrieval. Consistent with prior work observing modulations in task-evoked pupillary reactivity with task difficulty [56,61,62,64,95], pupillary reactivity modulated according to differences in problem difficulty, with the largest reactivity observed for small-split problems and the smallest reactivity observed for massive-split problems. Together, the present findings appear to align with the cognitive resource account of task-evoked pupillary reactivity such that pupil size is an overall aggregate of cognitive resource allocation during problem-solving, thus modulating proportionally to task difficulty [54–56]. These findings underscore the utility of task-evoked pupillary reactivity for objectively assessing arithmetic strategy during complex arithmetic performance. Given that self-reports of strategy use can negatively impact task performance, especially in low-performing individuals [96], using an objective index of arithmetic strategy has important implications for arithmetic cognition research.

Novel to the extant literature was the finding that higher aerobic fitness is related to better performance in processing the most challenging problems (small-split and large-split), which require the use of exact and approximate calculation procedures. Higher-aerobically-fit individuals exhibited shorter reaction time and larger task-evoked pupillary reactivity on these problems. These findings do not support the efficiency hypothesis for fitness-related differences in mathematics (as greater response accuracy would need to be observed in addition to shorter reaction time across all problems) and are instead consistent with the resource hypothesis. Likewise, previous studies observing support for the resource hypothesis have observed that individuals higher in fluid intelligence exhibit shorter reaction time and larger pupillary dilations on more demanding task conditions [56], which also aligns with work demonstrating higher aerobic fitness in preadolescents relates to superior execution of strategies during performance of learning and memory tasks [4,35]. This finding suggests that individuals higher in aerobic fitness have greater cognitive resources available to draw upon for employing exact and approximate arithmetic procedures to solve more challenging problems. Additionally, this finding suggests that college-aged adults higher in aerobic fitness flexibly modulate arithmetic strategies across problems and do not necessarily differ from low-fit individuals in applying the set of cognitive processes required in retrieval strategies (as evidenced by the lack of fitness-related difference in performance and pupillary reactivity on the massive-split problems). Our results give initial insight into the assumption that higher-fit individuals are more cognitively flexible to shift between procedural strategies. Future work in this area should examine how aerobic fitness modulates the switch costs related to shifting between retrieval, approximate, and exact arithmetic strategies. Thus, mathematics achievement differences may stem from aerobic fitness modulating cognitive resources available for solving more demanding problems that require more effortful procedural strategies (i.e., exact and approximate calculation). Although previous literature investigating the association of aerobic fitness and physical activity participation with academic achievement during college has used self-reported grade point averages [19,20], the present findings provide preliminary evidence to suggest that aerobic fitness—even in college-aged young adults—is associated with superior mathematics achievement. However, it is important to acknowledge the speculation of such an assertion given the present investigation did not also collect a measure of mathematics achievement. Nonetheless, activity-promoting interventions supporting physical activity participation and aerobic fitness—even during the college years—are necessary to address the drastic reduction in moderate-to-vigorous physical activity experienced during this time as such interventions could have implications for academic success in this population.

Further research is necessary to incorporate measures of mathematics achievement alongside neuroelectric indices of arithmetic processing, attention, and aspects of cognitive control to better understand the structure of the relationships with aerobic fitness across mathematics proficiency levels. Given the present finding that higher aerobic fitness is related to enhanced cognitive resources allocated on problems requiring exact and approximate arithmetic in college-aged young adults—a period when these processes are mature—further research is necessary to examine the relationship between aerobic fitness and arithmetic processing at various developmental stages to better elucidate how aerobic fitness may influence the maturation of cognitive mechanics underlying mathematical reasoning. Future research in this area should also seek to characterize baseline mathematics ability and exposure to formal mathematics courses/education to ensure similar levels of mathematical competence across individuals. Given that the present investigation used a sample of high-functioning college-aged adults enrolled at the same university with a similar number of years of education, and that arithmetic competencies are fully operational by sixth grade [48], it is unlikely that this presents as a confound within the current investigation. However, such an understanding has greater relevance when investigating other developmental stages prior to young adulthood since arithmetic competencies are still developing. Finally, as the present investigation used a cross-sectional approach, future research is necessary to understand how changes in physical activity levels and aerobic fitness manifest in changes to neural underpinnings subserving these arithmetic performance differences over time.

Beyond having direct implications for educational policy and academic achievement, these findings also provide preliminary evidence of the clinical implications of low numeracy. Because prevention of the leading causes of death (i.e., cardiovascular disease, cancer, obesity, diabetes) depends on taking action now to prevent later adverse health outcomes, those individuals low in numeracy (and as evidenced by this study low in cardiovascular health) may require alternative communication formats to engage in prevention behaviors as these individuals may process quantitative information differently. For instance, visual and graphic representations may make numerical relations more transparent and different methods of conveying quantitative information may have different effects on health behaviors (e.g., greater risk avoidance). Policymakers and federal guidelines recommending weekly and daily durations of physical activity fail to account for how those individuals lowest in cardiovascular health and engagement in preventative health behaviors may also be not able to fully understand risk probabilities and taking action based on quantitative information. With approximately 50% of people first seeking information about health and disease online independently [97], how do we know that people are understanding the numerical information they view online? Indeed, the determinants of health numeracy and health disparities are multifaceted. Nonetheless, future work in this vein may seek to test how interventions targeting cardiovascular health lead to improvements in understanding numerical information and examine how these enhancements lead to behavioral change (e.g., reducing sedentary activity) in daily life.

5. Conclusion

Collectively, using a well-powered sample of college-aged young adults, the present investigation demonstrated that aerobic fitness was associated with superior performance and enhanced allocation of cognitive resources during exact and approximate arithmetic procedures. That is, aerobic fitness appears to relate to aspects of arithmetic proficiency such that higher aerobic fitness is related to shorter reaction time and greater task-evoked pupillary reactivity on the most challenging problems. Thus, it may be that fitness-related differences in mathematics achievement stem from greater cognitive resources supporting superior execution of exact and approximate arithmetic strategies. To this end, the present findings have implications that extend well beyond the classroom. Indeed, poor mathematical competence—even in individuals with proficient literacy skills— is related to lower levels of educational attainment, employment status, and income [98–100]. Furthermore, superior quantitative knowledge and calculation abilities are related to attenuated age-related cognitive decline and higher levels of health literacy—and thus, are linked to positive health outcomes and overall well-being [101,102]. To this end, lower cardiovascular health (i.e., lower aerobic fitness) may be associated with altered neural processing of quantitative information and thus implicated in a compromised ability to engage in positive health behaviors—such as reading nutrition information, interpreting blood sugar readings and other clinical data, or even interpreting health risk probabilities. As a higher prevalence of cardiometabolic health risks (e.g., diabetes) is associated with low cardiovascular health, these preliminary findings point towards a possible relationship between disparities in health attributed to variations in processing of quantitative information. However, it is important to note that the determinants of disparities in health numeracy are complex and multiply determined. Although speculative, arithmetic processing may play into individuals' ability to maintain such health behaviors, thereby affecting their motivation to take action and engage in behaviors based on quantitative information. Thus, processing of quantitative information may increase or decrease the likelihood of action and behavioral change. Future work in this area will allow for the testing of interventions and alternative formats of conveying quantitative information in health messaging, such as verbal plus numerical or numerical plus graphical, to understand how these communication formats vary as a function of the characteristics of the target population. Accordingly, understanding activity-promoting interventions that modify health factors as well as mechanisms supporting and enhancing mathematical competence are essential for optimizing brain health and cognitive function across schools, workplaces, and health care settings.

Ethics statement

The study described herein was conducted with prior approval of the Institutional Review Board at Michigan State University. All participants signed an Informed Consent form prior to participation in the study and their rights were protected.

Declaration of Competing Interest

We wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us.

We confirm that we have given due consideration to the protection of intellectual property associated with this work and that there are no impediments to publication, including the timing of publication, with respect to intellectual property. In so doing we confirm that we have followed the regulations of our institutions concerning intellectual property.

We further confirm that any aspect of the work covered in this manuscript that has involved either experimental animals or human patients has been conducted with the ethical approval of all relevant bodies and that such approvals are acknowledged within the manuscript.

We understand that the Corresponding Author is the sole contact for the Editorial process (including Editorial Manager and direct communications with the office). He/she is responsible for communicating with the other authors about progress, submissions of revisions and final approval of proofs. We confirm that we have provided a current, correct email address which is accessible by the Corresponding Author and which has been configured to accept email from (amanda.mcgowan@asc.upenn.edu)

Signed by all authors as follows:

Acknowledgments

Support for the preparation of this manuscript was provided by a Dissertation Completion Fellowship awarded to A. L. McGowan through The Graduate School at Michigan State University. Funding sources had no involvement in the design, collection, analysis and interpretation of data, or in the writing of the manuscript and decision to submit for publication. This research would not have been completed without the efforts and enthusiasm of a number of undergraduate research assistants who assisted with data collection: Madeline Allen, Madeleine Barrera, David Gasser, Morgan Ham, Mallory Martlock, Will Shriver, Katie Voisard, and Kelly Zorn.

References

[1] 2018 Physical Activity Guidelines Advisory Committee. 2018 Physical Activity Guidelines Advisory Committee Scientific Report. Washington, DC: U.S. Department of Health and Human Services, 2018. http://health.gov/sites/default/files/2019-09/PAG_Advisory_Committee_Report.pdf.

[2] J.D. Barnes, C. Cameron, V. Carson, J.P. Chaput, R.C. Colley, G.E. Faulkner, …, M.S. Tremblay, Results from Canada's 2018 report card on physical activity for children and youth, J. Phys. Activity and Health 15 (s2) (2009) S328–S330.

[3] M.A.I. Åberg, N.L. Pedersen, K. Torén, M. Svartengren, B. Bäckstrand, T. Johnsson, C.M. Cooper-Kuhn, N.D. Åberg, M. Nilsson, H.G. Kuhn, Cardiovascular fitness is associated with cognition in young adulthood, Proc. Natl. Acad. Sci. U. S. A. 106 (2009) 20906–20911, https://doi.org/10.1073/pnas.0905307106.

[4] L. Chaddock, K.I. Erickson, R.S. Prakash, J.S. Kim, M.W. Voss, M. VanPatter, M. B. Pontifex, L.B. Raine, A. Konkel, C.H. Hillman, N.J. Cohen, A.F. Kramer, A neuroimaging investigation of the association between aerobic fitness, hippocampal volume, and memory performance in preadolescent children, Brain Res. 1358 (2010) 172–183, https://doi.org/10.1016/j.brainres.2010.08.049.

[5] L. Chaddock, M.B. Pontifex, C.H. Hillman, A.F. Kramer, A review of the relation of aerobic fitness and physical activity to brain structure and function in children, J. Int. Neuropsychol. Soc. 17 (2011) 975–985, https://doi.org/10.1017/S1355617711000567.

[6] O. Dupuy, C.J. Gauthier, S.A. Fraser, L. Desjardins-Crèpeau, M. Desjardins, S. Mekary, F. Lesage, R.D. Hoge, P. Pouliot, L. Bherer, Higher levels of cardiovascular fitness are associated with better executive function and prefrontal oxygenation in younger and older women, Front. Hum. Neurosci. (2015) 9, https://doi.org/10.3389/fnhum.2015.00066.

[7] C.H. Hillman, E.P. Weiss, J.M. Hagberg, B.D. Hatfield, The relationship of age and cardiovascular fitness to cognitive and motor processes, Psychophysiology 39 (2002) 303–312.

[8] M. Hogan, M. Kiefer, S. Kubesch, P. Collins, L. Kilmartin, M. Brosnan, The interactive effects of physical fitness and acute aerobic exercise on electrophysiological coherence and cognitive performance in adolescents, Exp. Brain Res. 229 (2013) 85–96, https://doi.org/10.1007/s00221-013-3595-0.

[9] T. Huang, J. Tarp, S.L. Domazet, A.K. Thorsen, K. Froberg, L.B. Andersen, A. Bugge, Associations of adiposity and aerobic fitness with executive function and math performance in Danish adolescents, J. Pediatr. 167 (2015) 810–815, https://doi.org/10.1016/j.jpeds.2015.07.009.

[10] J.R. Ruiz, F.B. Ortega, R. Castillo, M. Martín-Matillas, L. Kwak, G. Vicente-Rodríguez, J. Noriega, P. Tercedor, M. Sjöström, L.A. Moreno, Physical activity, fitness, weight status, and cognitive performance in adolescents, J. Pediatr. 157 (2010) 917–922, https://doi.org/10.1016/j.jpeds.2010.06.026, e5.

[11] T.-.F. Song, L. Chi, C.-.H. Chu, F.-.T. Chen, C. Zhou, Y.-.K. Chang, Obesity, cardiovascular fitness, and inhibition function: an electrophysiological study, Front. Psychol. 7 (2016), https://doi.org/10.3389/fpsyg.2016.01124.

[12] D.M. Castelli, C.H. Hillman, S.M. Buck, H.E. Erwin, Physical fitness and academic achievement in third- and fifth-grade students, J. Sport Exerc. Psychol. 29 (2007) 239–252.

[13] C.L. Davis, S. Cooper, Fitness, fatness, cognition, behavior, and academic achievement among overweight children: do cross-sectional associations correspond to exercise trial outcomes? Prev. Med. 52 (2011) https://doi.org/10.1016/j.ypmed.2011.01.020. S65–S69.

[14] B.M. Eveland-Sayers, R.S. Farley, D.K. Fuller, D.W. Morgan, J.L. Caputo, Physical fitness and academic achievement in elementary school children, J. Phys. Act. Health. 6 (2009) 99–104, https://doi.org/10.1123/jpah.6.1.99.

[15] Á.Logi Kristjánsson, I.Dóra Sigfúsdóttir, J.P. Allegrante, Health behavior and academic achievement among adolescents: the relative contribution of dietary habits, physical activity, body mass index, and self-esteem, Health Educ. Behav. 37 (2010) 51–64, https://doi.org/10.1177/1090198107313481.

[16] R.A. London, S. Castrechini, A longitudinal examination of the link between youth physical fitness and academic achievement, J. Sch. Health. 81 (2011) 400–408, https://doi.org/10.1111/j.1746-1561.2011.00608.x.

[17] N. Morita, T. Nakajima, K. Okita, T. Ishihara, M. Sagawa, K. Yamatsu, Relationships among fitness, obesity, screen time and academic achievement in Japanese adolescents, Physiol. Behav. 163 (2016) 161–166, https://doi.org/10.1016/j.physbeh.2016.04.055.

[18] V. Suchert, R. Hanewinkel, B. Isensee, Longitudinal relationships of fitness, physical activity, and weight status with academic achievement in adolescents, J. Sch. Health. 86 (2016) 734–741, https://doi.org/10.1111/josh.12424.

[19] X.D. Keating, R. Shangguan, K. Xiao, X. Gao, C. Sheehan, L. Wang, J. Colburn, Y. Fan, F. Wu, Tracking changes of Chinese pre-service teachers' aerobic fitness, body mass index, and grade point average over 4-years of college, Int. J. Environ. Res. Public. Health. (2019) 16, https://doi.org/10.3390/ijerph16060966.

[20] K.L. Vasold, S.J. Deere, J.M. Pivarnik, Club and intramural sports participation and college student academic success, Recreat. Sports J. 43 (2019) 55–66, https://doi.org/10.1177/1558866119840085.

[21] L.C. Blom, J. Alvarez, L. Zhang, J. Kolbo, Associations between health-related physical fitness, academic achievement and selected academic behaviors of elementary and middle school students in the State of Mississippi, ICHPER-SD J. Res. 6 (2011) 13–19.

[22] V.R. Chomitz, M.M. Slining, R.J. McGowan, S.E. Mitchell, G.F. Dawson, K. A. Hacker, Is there a relationship between physical fitness and academic achievement? Positive results from public school children in the northeastern United States, J. Sch. Health. 79 (2009) 30–37, https://doi.org/10.1111/j.1746-1561.2008.00371.x.

[23] G. Colquitt, J. Langdon, T. Hires, T. Pritchard, The relationship between fitness and academic achievement in an urban school setting, Sport Sci. Pract. Asp. (2011) 5–13.

[24] J.W. de Greeff, E. Hartman, M.J. Mullender-Wijnsma, R.J. Bosker, S. Doolaard, C. Visscher, Physical fitness and academic performance in primary school children with and without a social disadvantage, Health Educ. Res. 29 (2014) 853–860, https://doi.org/10.1093/her/cyu043.

[25] I.K. Desai, A.V. Kurpad, V.R. Chomitz, T. Thomas, Aerobic fitness, micronutrient status, and academic achievement in indian school-aged children, PLoS ONE 10 (2015), https://doi.org/10.1371/journal.pone.0122487 e0122487.

[26] D.M. Hansen, S.D. Herrmann, K. Lambourne, J. Lee, J.E. Donnelly, Linear/nonlinear relations of activity and fitness with children's academic achievement, Med. Sci. Sports Exerc. 46 (2014) 2279–2285, https://doi.org/10.1249/MSS.0000000000000362.

[27] R.R. Rauner, R.W. Walters, M. Avery, T.J. Wanser, Evidence that aerobic fitness is more salient than weight status in predicting standardized math and reading outcomes in fourth-through eighth-grade students, J. Pediatr. 163 (2013) 344–348.

[28] R.E. Dustman, R.Y. Emmerson, R.O. Ruhling, D.E. Shearer, L.A. Steinhaus, S. C. Johnson, H.W. Bonekat, J.W. Shigeoka, Age and fitness effects on EEG, ERPs, visual sensitivity, and cognition, Neurobiol. Aging. 11 (1990) 193–200, https://doi.org/10.1016/0197-4580(90)90545-B.

[29] R.Y. Emmerson, R.E. Dustman, D.E. Shearer, C.W. Turner, P3 latency and symbol digit performance correlations in aging, Exp. Aging Res. 15 (1989) 151–159, https://doi.org/10.1080/03610738908259769.

[30] C.H. Hillman, D.M. Castelli, S.M. Buck, Aerobic fitness and neurocognitive function in healthy preadolescent children, Med. Sci. Sports Exerc. 37 (2005) 1967–1974.

[31] R.D. Moore, C.-.T. Wu, M.B. Pontifex, K.C. O'Leary, M.R. Scudder, L.B. Raine, C. R. Johnson, C.H. Hillman, Aerobic fitness and intra-individual variability of neurocognition in preadolescent children, Brain Cogn 82 (2013) 43–57, https://doi.org/10.1016/j.bandc.2013.02.006.

[32] M.B. Pontifex, L.B. Raine, C.R. Johnson, L. Chaddock, M.W. Voss, N.J. Cohen, A. F. Kramer, C.H. Hillman, Cardiorespiratory fitness and the flexible modulation of cognitive control in preadolescent children, J. Cogn. Neurosci. 23 (2011) 1332–1345, https://doi.org/10.1162/jocn.2010.21528.

[33] C.-.H. Wang, C.-.M. Shih, C.-.L. Tsai, The relation between aerobic fitness and cognitive performance: is it mediated by brain potentials? J. Psychophysiol. 30 (2016) 102–113, https://doi.org/10.1027/0269-8803/a000159.

[34] R.D. Moore, E.S. Drollette, M.R. Scudder, A. Bharij, C.H. Hillman, The influence of cardiorespiratory fitness on strategic, behavioral, and electrophysiological indices of arithmetic cognition in preadolescent children, Front. Hum. Neurosci. 8 (2014), https://doi.org/10.3389/fnhum.2014.00258.

[35] L.B. Raine, H.K. Lee, B.J. Saliba, L. Chaddock-Heyman, C.H. Hillman, A. F. Kramer, The influence of childhood aerobic fitness on learning and memory, PLoS ONE 8 (2013) e72666, https://doi.org/10.1371/journal.pone.0072666.

[36] M.M. Herting, B.J. Nagel, Aerobic fitness relates to learning on a virtual Morris Water Task and hippocampal volume in adolescents, Behav. Brain Res. 233 (2012) 517–525, https://doi.org/10.1016/j.bbr.2012.05.012.

[37] S.-.C. Kao, E.S. Drollette, M.R. Scudder, L.B. Raine, D.R. Westfall, M.B. Pontifex, C.H. Hillman, Aerobic fitness is associated with cognitive control strategy in preadolescent children, J. Mot. Behav. 49 (2017) 150–162.

[38] C.H. Hillman, S.M. Buck, J.R. Themanson, M.B. Pontifex, D.M. Castelli, Aerobic fitness and cognitive development: event-related brain potential and task performance indices of executive control in preadolescent children, Dev. Psychol. 45 (2009) 114–129, https://doi.org/10.1037/a0014437.

[39] K. Kamijo, H. Masaki, Fitness and ERP indices of cognitive control mode during task preparation in preadolescent children, Front. Hum. Neurosci. 10 (2016) 441.

[40] A. Luque-Casado, P. Perakakis, C.H. Hillman, S.-.C. Kao, F. Llorens, P.A. M. Guerra, D. Sanabria, Differences in sustained attention capacity as a function of aerobic fitness, Med. Sci. Sports Exerc. 48 (2016) 887–895, https://doi.org/10.1249/MSS.0000000000000857.

[41] M.B. Pontifex, C.H. Hillman, J. Polich, Age, physical fitness, and attention: P3a and P3b, Psychophysiology 46 (2009) 379–387, https://doi.org/10.1111/j.1469-8986.2008.00782.x.

[42] S. Ahern, J. Beatty, Pupillary responses during information processing vary with Scholastic Aptitude Test scores, Science 205 (1979) 1289–1292.

[43] N.C. Jordan, L.B. Hanich, D. Kaplan, Arithmetic fact mastery in young children: a longitudinal investigation, J. Exp. Child Psychol. 85 (2003) 103–119, https://doi.org/10.1016/S0022-0965(03)00032-8.

[44] Looi, C. et al. (2016), "The Neuroscience of Mathematical Cognition and Learning", OECD Education Working Papers, No. 136, OECD Publishing, Paris. https://doi.org/10.1787/5jlwmn3ntbr7-en.

[45] M. Kutner, E. Greenburg, Y. Jin, C. Paulsen, The Health Literacy of America's Adults: results from the 2003 National Assessment of Adult Literacy. NCES 2006-483, Natl. Cent. Educ. Stat. (2006).

[46] V.M. Montori, R.L. Rothman, Weakness in Numbers, J. Gen. Intern. Med. 20 (2005) 1071–1072, https://doi.org/10.1111/j.1525-1497.2005.051498.x.

[47] R.S. Siegler, The perils of averaging data over strategies: an example from children's addition, J. Exp. Psychol. Gen. 116 (1987) 250.

[48] I. Imbo, A. Vandierendonck, Effects of problem size, operation, and working-memory span on simple-arithmetic strategies: differences between children and adults? Psychol. Res. 72 (2008) 331–346, https://doi.org/10.1007/s00426-007-0112-8.

[49] R.S. Siegler, C. Shipley, Variation, selection, and cognitive change, Dev. Cogn. Competence New Approaches Process Model. (1995) 31–76.

[50] S.A. Hecht, Group differences in adult simple arithmetic: good retrievers, not-so-good retrievers, and perfectionists, Mem. Cognit. 34 (2006) 207–216.

[51] R. El Yagoubi, P. Lemaire, M. Besson, Different brain mechanisms mediate two strategies in arithmetic: evidence from event-related brain potentials, Neuropsychologia 41 (2003) 855–862.

[52] W. He, W. Luo, H. He, X. Chen, D. Zhang, N170 effects during exact and approximate calculation tasks: an ERP study, Neuroreport 22 (2011) 437–441, https://doi.org/10.1097/WNR.0b013e32834702c1.

[53] W. Luo, D. Liu, W. He, W. Tao, Y. Luo, Dissociated brain potentials for two calculation strategies, Neuroreport 20 (2009) 360–364, https://doi.org/10.1097/WNR.0b013e328323d737.

[54] M.A. Just, P.A. Carpenter, A. Miyake, Neuroindices of cognitive workload: neuroimaging, pupillometric and event-related potential studies of brain work, Theor. Issues Ergon. Sci. 4 (2003) 56–88.

[55] N. Unsworth, M.K. Robison, Individual differences in the allocation of attention to items in working memory: evidence from pupillometry, Psychon. Bull. Rev. 22 (2015) 757–765, https://doi.org/10.3758/s13423-014-0747-6.

[56] E. van der Meer, R. Beyer, J. Horn, M. Foth, B. Bornemann, J. Ries, J. Kramer, E. Warmuth, H.R. Heekeren, I. Wartenburger, Resource allocation and fluid intelligence: insights from pupillometry, Psychophysiology 47 (2010) 158–169, https://doi.org/10.1111/j.1469-8986.2009.00884.x.

[57] J. Beatty, Task-evoked pupillary responses, processing load, and the structure of processing resources, Psychol. Bull. 91 (1982) 276–292, https://doi.org/10.1037/0033-2909.91.2.276.

[58] J. Beatty, B. Lucero-Wagoner, The pupillary system, Handb. Psychophysiol. 2 (2000) 142–162.

[59] E.H. Hess, J.M. Polt, Pupil size in relation to mental activity during simple problem-solving, Science 143 (1964) 1190–1192, https://doi.org/10.1126/science.143.3611.1190.

[60] D. Kahneman, J. Beatty, Pupil diameter and load on memory, Science 154 (1966) 1583–1585.

[61] B. Laeng, M. Ørbo, T. Holmlund, M. Miozzo, Pupillary Stroop effects, Cogn. Process. 12 (2011) 13–21, https://doi.org/10.1007/s10339-010-0370-z.

[62] A.L. McGowan, M.C. Chandler, J.W. Brascamp, M.B. Pontifex, Pupillometric indices of locus-coeruleus activation are not modulated following single bouts of exercise, Int. J. Psychophysiol. 140 (2019) 41–52, https://doi.org/10.1016/j.ijpsycho.2019.04.004.

[63] G. Porter, T. Troscianko, I.D. Gilchrist, Effort during visual search and counting: insights from pupillometry, Q. J. Exp. Psychol. 60 (2007) 211–229, https://doi.org/10.1080/17470210600673818.

[64] C. Scharinger, A. Soutschek, T. Schubert, P. Gerjets, When flanker meets the n-back: what EEG and pupil dilation data reveal about the interplay between the two central-executive working memory functions inhibition and updating, Psychophysiology 52 (2015) 1293–1304, https://doi.org/10.1111/psyp.12500.

[65] E.P. Kirk, M.H. Ashcraft, Telling stories: the perils and promise of using verbal reports to study math strategies, J. Exp. Psychol. Learn. Mem. Cogn. 27 (2001) 157.

[66] A.S. Kaufman, N.L. Kaufman, Kaufman Brief Intelligence Test Manual, American Guidance Service, Circle Pines, MN, 1990.

[67] M. Niedeggen, F. Rösler, K. Jost, Processing of incongruous mental calculation problems: evidence for an arithmetic N400 effect, Psychophysiology 36 (1999) 307–324.

[68] N.J. Zbrodoff, G.D. Logan, When it hurts to be misled: a Stroop-like effect in a simple addition production task, Mem. Cognit. 28 (2000) 1–7.

[69] S.M. Buck, C.H. Hillman, D.M. Castelli, The relation of aerobic fitness to Stroop task performance in preadolescent children, Med. Sci. Sports Exerc. 40 (2008) 166–172.

[70] K. Kamijo, Y. Takeda, General physical activity levels influence positive and negative priming effects in young adults, Clin. Neurophysiol. 120 (2009) 511–519, https://doi.org/10.1016/j.clinph.2008.11.022.

[71] C.-.H. Wang, D. Moreau, C.-.T. Yang, J.-.T. Lin, Y.-.Y. Tsai, C.-.L. Tsai, The influence of aerobic fitness on top-down and bottom-up mechanisms of interference control, Neuropsychology 33 (2019) 245–255, https://doi.org/10.1037/neu0000507.

[72] J.I.D. Campbell, Conditions of error priming in number-fact retrieval, Mem. Cognit. 19 (1991) 197–209.

[73] S. Stroth, S. Kubesch, K. Keiterle, M. Ruchsow, R. Heim, M. Kiefer, Physical fitness, but not acute exercise modulates event-related potential indices for executive control in healthy adolescents, Brain Res. 1269 (2009) 114–124.

[74] L. Kjønniksen, T. Torsheim, B. Wold, Tracking of leisure-time physical activity during adolescence and young adulthood: a 10-year longitudinal study, Int. J. Behav. Nutr. Phys. Act. 5 (2008) 69, https://doi.org/10.1186/1479-5868-5-69.

[75] Y. Meckel, Y. Galily, D. Nemet, A. Eliakim, Changes in weight indexes and aerobic fitness of physical education students over three years of college, J. Hum. Sport Exerc. 6 (2011) 112–121.
[76] S. Thomas, J. Reading, R.J. Shephard, Revision of the physical activity readiness questionnaire (PAR-Q), Can. J. Sport Sci. 17 (1992) 338–345.
[77] E. Shvartz, R.C. Reibold, Aerobic fitness norms for males and females aged 6 to 75 years: a review, Aviat. Space Environ. Med. 61 (1990) 3–11.
[78] J.-A. LeFevre, J. Bisanz, K.E. Daley, L. Buffone, S.L. Greenham, G.S. Sadesky, Multiple routes to solution of single-digit multiplication problems, J. Exp. Psychol. Gen. 125 (1996) 284.
[79] M. Carr, H. Davis, Gender differences in arithmetic strategy use: a function of skill and preference, Contemp. Educ. Psychol. 26 (2001) 330–347.
[80] J.I.D. Campbell, Handbook of Mathematical Cognition, Psychology Press, 2005.
[81] P. Lemaire, M. Fayol, When plausibility judgments supersede fact retrieval: the example of the odd-even effect on product verification, Mem. Cognit. 23 (1995) 34–48, https://doi.org/10.3758/BF03210555.
[82] P. Lemaire, L. Reder, What affects strategy selection in arithmetic? The example of parity and five effects on product verification, Mem. Cognit. 27 (1999) 364–382, https://doi.org/10.3758/BF03211420.
[83] A. Delorme, S. Makeig, EEGLAB: an open source toolbox for analysis of single-trial EEG dynamics, J. Neurosci. Methods. 134 (2004) 9–21, https://doi.org/10.1016/j.jneumeth.2003.10.009.
[84] T. Knapen, J.W. de Gee, J.W. Brascamp, S. Nuiten, S. Hoppenbrouwers, J. Theeuwes, Cognitive and ocular factors jointly determine pupil responses under equiluminance, PLoS ONE 11 (2016), https://doi.org/10.1371/journal.pone.0155574 e0155574.
[85] P.R. Murphy, I.H. Robertson, J.H. Balsters, R.G. O'Connell, Pupillometry and P3 index the locus coeruleus–noradrenergic arousal function in humans, Psychophysiology 48 (2011) 1532–1543, https://doi.org/10.1111/j.1469-8986.2011.01226.x.
[86] P.R. Murphy, R.G. O'Connell, M. O'Sullivan, I.H. Robertson, J.H. Balsters, Pupil diameter covaries with BOLD activity in human locus coeruleus, Hum. Brain Mapp. 35 (2014) 4140–4154, https://doi.org/10.1002/hbm.22466.
[87] R. Core Team, R: a Language and Environment for Statistical Computing, 2019. Vienna, Austria, https://www.R-project.org/.
[88] R. Lenth, H. Singmann, J. Love, P. Buerkner, M. Herve, emmeans: estimated marginal means. R package version 1.4. 4, Am. Stat. 34 (4) (2020) 216–221.
[89] J. Pinheiro, nlme: linear and nonlinear mixed effects models. R package version 3.1-96, Httpcran R-Proj, Orgwebpackagesnlme (2009).
[90] T.T. Shigeta, A.A. Leahy, J.J. Smith, N. Eather, D.R. Lubans, C.H. Hillman, Cardiorespiratory and muscular fitness associations with older adolescent cognitive control: fitness associations with adolescent cognitive control, J. Sport Health Sci. (2020).
[91] N. Bolger, J.-.P. Laurenceau, Intensive Longitudinal methods: An introduction to Diary and Experience Sampling Research, Guilford Press, 2013.
[92] B.L. Alderman, R.L. Olson, The relation of aerobic fitness to cognitive control and heart rate variability: a neurovisceral integration study, Biol. Psychol. 99 (2014) 26–33, https://doi.org/10.1016/j.biopsycho.2014.02.007.
[93] J. Mora-Gonzalez, I. Esteban-Cornejo, P. Solis-Urra, J.H. Migueles, C. Cadenas-Sanchez, P. Molina-Garcia, M. Rodriguez-Ayllon, C.H. Hillman, A. Catena, M. B. Pontifex, F.B. Ortega, Fitness, physical activity, sedentary time, inhibitory control, and neuroelectric activity in children with overweight or obesity: the ActiveBrains project, Psychophysiology 57 (2020) e13579, https://doi.org/10.1111/psyp.13579.
[94] D.R. Westfall, A.K. Gejl, J. Tarp, N. Wedderkopp, A.F. Kramer, C.H. Hillman, A. Bugge, Associations between aerobic fitness and cognitive control in adolescents, Front. Psychol. 9 (2018), https://doi.org/10.3389/fpsyg.2018.01298.
[95] H.D. Critchley, J. Tang, D. Glaser, B. Butterworth, R.J. Dolan, Anterior cingulate activity during error and autonomic response, Neuroimage 27 (2005) 885–895.
[96] B.L. Smith-Chant, J.-.A. LeFevre, Doing as they are told and telling it like it is: self-reports in mental arithmetic, Mem. Cognit. 31 (2003) 516–528.
[97] B.W. Hesse, D.E. Nelson, G.L. Kreps, R.T. Croyle, N.K. Arora, B.K. Rimer, K. Viswanath, Trust and sources of health information: the impact of the Internet and its implications for health care providers: findings from the first Health Information National Trends Survey, Arch. Intern. Med. 165 (2005) 2618–2624.
[98] G.J. Duncan, C.J. Dowsett, A. Claessens, K. Magnuson, A.C. Huston, P. Klebanov, L.S. Pagani, L. Feinstein, M. Engel, J. Brooks-Gunn, H. Sexton, K. Duckworth, C. Japel, School readiness and later achievement, Dev. Psychol. 43 (2007) 1428–1446, https://doi.org/10.1037/0012-1649.43.6.1428.
[99] D.C. Geary, Consequences, characteristics, and causes of mathematical learning disabilities and persistent low achievement in mathematics, J. Dev. Behav. Pediatr. JDBP. 32 (2011) 250.
[100] N.C. Jordan, D. Kaplan, C. Ramineni, M.N. Locuniak, Early math matters: kindergarten number competence and later mathematics outcomes, Dev. Psychol. 45 (2009) 850.
[101] M. Delazer, G. Kemmler, T. Benke, Health numeracy and cognitive decline in advanced age, Aging Neuropsychol. Cogn. 20 (2013) 639–659.
[102] V.F. Reyna, C.J. Brainerd, The importance of mathematics in health and human judgment: numeracy, risk communication, and medical decision making, Learn. Individ. Differ. 17 (2007) 147–159, https://doi.org/10.1016/j.lindif.2007.03.010.