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Aerobic Fitness Relates to Superior Exact and Approximate
Arithmetic Processing in College-Aged Adults

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Highlights

- Higher-fit individuals processed arithmetic problems faster.
- Higher-fit individuals allocated more cognitive resources during difficult problems.
- Fitness-related differences in mathematics achievement stem from cognitive resource differences.
- Cardiovascular health may be implicated in differential processing of quantitative information.
- Improving cardiovascular health may help address disparities in health numeracy.

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.

Keywords: cardiorespiratory fitness, arithmetic strategy, health numeracy, young adults, mathematics achievement

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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 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 underlying 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 summing the $6 + 3$ and then summing 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 summing 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 ± 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 [redacted for review] 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 $\pm$ SD).

Measure	All	Females	Males
N [†]	138	74	63
Age (years)	18.9 $\pm$ 1.0 [18 – 26]	18.9 $\pm$ 1.2 [18 – 26]	19.0 $\pm$ 0.8 [18 – 21]
Education (years)	12.9 $\pm$ 1.3 [12 – 18]	13.1 $\pm$ 1.6 [12 – 18]	12.7 $\pm$ 1.0 [12 – 16]
Nonwhite (%) [†]	17.5	14.9	20.6
VO _{2max} (ml/kg/min)	44.8 $\pm$ 10.2 [23.5 – 67.8]	39.5 $\pm$ 7.1 [23.5 – 56.6]	50.9 $\pm$ 8.3 [24 – 67.8]
VO _{2max} Percentile	51.4 $\pm$ 37.0 [3 – 99]	42.9 $\pm$ 35.9 [3 – 99]	61.7 $\pm$ 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 Figure 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 ($\geq 95\%$). 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 Figure 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 minutes and 20 seconds to complete for a total task duration of 10 minutes. 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.

Complex Arithmetic Task

Figure 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.

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 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 1,200 ms around the response and baseline corrected to the first stimulus presentation using the -1,000 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 1,200 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* [88], *emmeans* [89], and *nlme* [90] packages in R version 4.0.2 [88] with $\alpha = .05$. Using recently-published findings in older adolescents [91] and college-aged adults [3], we followed procedures for power analysis in multilevel models [92] and find that with a sample of 120 participants, a significant between-person association between fitness and cognitive function is observed in 90% of 1,000 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.

Table 2. Correlations of demographic factors and task performance variables.

Variable	<i>M</i>	<i>SD</i>	1	2	3	4	5	6	7	8	9	10	11	12
1. Age	18.93	1.10												
2. Sex	---	---	.02											
3. Nonwhite	---	---	-.15	.08										
4. Fitness	51.41	32.33	.19*	.29**	-.14									
5. Small RT	602.67	194.43	.11	-.00	-.01	-.08								
6. Large RT	499.56	164.09	.11	-.18*	-.00	-.15	.91**							
7. Massive RT	381.45	125.53	.08	-.20*	.06	-.21*	.71**	.84**						
8. Small ACC	72.04	10.27	.10	.39**	-.13	.11	.08	-.12	-.24**					
9. Large ACC	88.48	6.61	-.04	.18*	-.31**	.11	-.03	-.22*	-.19*	.49**				
10. Massive ACC	95.87	2.86	.01	.08	-.09	.03	-.17*	-.28**	-.26**	.22*	.48**			
11. Small Pupil	69.19	36.13	-.01	.09	-.15	.13	-.01	-.10	-.10	.21*	.15	-.08		
12. Large Pupil	45.98	25.87	.06	.10	-.10	.25**	-.08	-.14	-.14	.19*	.06	-.06	.55**	
13. Massive Pupil	26.14	26.11	-.05	.16	-.02	-.01	-.04	-.12	-.18*	-.04	.00	-.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 $p < 0.001$

3.1 Reaction Time

We ran multilevel models to examine whether fitness was associated with reaction time (see Table 3, Figure 2A). Individuals higher in aerobic fitness responded faster than those lower in aerobic fitness ($b = -0.95$, $p < 0.001$). The interaction of Split $\times$ 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, Figure 2B). Fitness was unrelated to response accuracy ($b = 0.002$, $p = 0.82$). The model would not converge with the inclusion of a Split $\times$ 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 ($b = 0.23$, $p = 0.42$). Males responded more accurately than females ($b = 3.6$, $p < 0.001$).

Figure 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.

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

4. Discussion

The aim of the present investigation was to determine the extent to 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 [9,40,41,93–95]. 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 [56,61,62,64,96], 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 [97], 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 [98], *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.

4.1 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 [99–101].

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 [102,103]. 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.

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