

Aerobic Fitness Unrelated to Acquisition of Spatial Relational Memory in College-Aged Adults

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While compelling evidence indicates that poorer aerobic fitness relates to impairments in retrieving information from hippocampal-dependent memory, there is a paucity of research on how aerobic fitness relates to the acquisition of such relational information. Accordingly, the present investigation examined the association between aerobic fitness and the rate of encoding spatial relational memory—assessed using a maximal oxygen consumption test and a spatial configuration task—in a sample of 152 college-aged adults. The findings from this investigation revealed no association between aerobic fitness and the acquisition of spatial relational memory. These findings have implications for how aerobic fitness is characterized with regard to memory, such that aerobic fitness does not appear to relate to the rate of learning spatial-relational information; however, given previously reported evidence, aerobic fitness may be associated with a greater ability to recall relational information from memory.

Keywords: hippocampal-dependent memory, memory acquisition, maximal oxygen consumption, spatial configuration

Over the past several decades, converging evidence across both human and animal models has demonstrated the detrimental effects of a sedentary lifestyle. Both the American (2018 Physical Activity Guidelines Advisory Committee, 2018) and Canadian (ParticipACTION, 2018) physical activity directives assert the importance of physical activity not only for physical health, but also for brain health—and a recent report from the World Health Organization (2019) lists increasing aerobic physical activity as the number one recommendation to reduce the risk of cognitive decline and dementia. As the implication is that these aerobic physical activities be sustained in a chronic and habitual manner, the physical health-related attribute of aerobic fitness is of particular interest. That is, although there is a genetic component to the attribute of aerobic fitness, physical activity of an aerobic nature is the antecedent behavior that directly relates to the acquisition of the attribute of aerobic fitness (Aadland, Jepsen, Andersen, & Anderssen, 2013; Ainsworth, Berry, Schnyder, & Vickers, 1992; McMurray, Bangdiwala, Harrell, & Amorim, 2008). Thus, aerobic fitness provides a means of gaining insight into how differences in chronic and habitual aerobic physical activity behaviors may accumulate over the course of many years or even decades to impact aspects of cognition. Interestingly, prior work has demonstrated that, even within cognitively healthy college-aged adults, individuals with lower levels of aerobic fitness demonstrate relatively poor cognitive performance in areas such as learning and memory compared with those who are more aerobically fit (Baym et al., 2014; Hillman, Erickson, & Kramer, 2008; Pontifex, Gwizdala, Parks, Pfeiffer, & Fenn, 2016; Pontifex et al., 2014; Rigdon & Loprinzi, 2019). However, despite these broad-based

claims regarding the importance of physical health behaviors (e.g., physical activity) and the related attributes (i.e., aerobic fitness) for supporting memory function, the extant literature has largely focused only upon the retrieval of information from long-term memory. Yet, information extraction is only one component of the construct of memory that is ultimately dependent upon the preceding abilities to acquire and encode the information into memory (Abel & Lattal, 2001)—and as the field of research into health neuroscience continues to grow, it is essential to understand the extent to which the health-related attribute of aerobic fitness relates to such preceding abilities. Accordingly, the aim of the present investigation was to specifically examine the relation between aerobic fitness and the rate of spatial relational memory acquisition.

Understanding the factors involved in optimizing the effectiveness of memory function is essential, given the vital importance of these processes in daily functioning, spatial navigation, classroom-based learning, and approaches to problem-solving. In particular, a great deal of research has focused upon hippocampal-dependent memory, given its role in encoding and retrieving relational memories (i.e., how and why specific people, places, and things are linked) to support goal-directed behaviors and daily interactions (Squire, 1992). More specifically, relational memory can be conceptualized as the binding of pieces of information to constitute larger representations of scenes, events, or situations (Cohen et al., 1999; Squire, 1992). Indeed, developing cognitive representations of spatial configurations within an environment—a process thought to be predominantly subserved by the hippocampus (Holzschneider, Wolbers, Röder, & Hötting, 2012)—forms the basis for navigating our environment to optimize and flexibly adapt our path to achieve a goal (Eichenbaum, 2000). Interestingly, an extensive body of literature in rodent models has focused upon the impact of increasing aerobic physical activity—and, subsequently, increasing levels of aerobic fitness—as it relates to spatial memory and the hippocampus (Vaynman & Gomez-Pinilla, 2006). Such

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investigations have demonstrated that increasing aerobic physical activity relates to enhancements in the retrieval of spatial memory, which co-occurs with the creation of new neurons and blood vessels within the dentate gyrus of the hippocampus (Creer, Romberg, Saksida, van Praag, & Bussey, 2010; Kobilko et al., 2011; van Praag, Christie, Sejnowski, & Gage, 1999; Uysal et al., 2005; Vaynman, Ying, & Gomez-Pinilla, 2004). In addition, long-term voluntary running (and subsequent increases in aerobic fitness) has been associated with increases in dendritic spine density, not only in the dentate gyrus and the CA1 region of the rat hippocampus, but also in the entorhinal cortex—a parahippocampal area traditionally associated with spatial/navigational memory (Stranahan, Khalil, & Gould, 2007). Research in human models has observed similar findings, with poorer aerobic fitness relating to lower relational memory performance (Baym et al., 2014; Pontifex et al., 2014) and smaller hippocampal volume (Chaddock et al., 2010; Erickson et al., 2009). Further, longitudinal aerobic physical activity interventions that enhance aerobic fitness have been shown to result in enhancements in the retrieval of hippocampal-dependent relational information (Monti, Hillman, & Cohen, 2012) and attenuation of age-related hippocampal volume loss (Erickson et al., 2011). In addition, a recent systematic review found a positive relationship between aerobic fitness and memory function in 15 of 17 investigations in this area (Rigdon & Loprinzi, 2019). Taken together, these investigations provide evidence to indicate that the retrieval of relational memory and the integrity of its underlying neural structures are influenced by the health-related attribute of aerobic fitness.

Given such evidence, it is perhaps unsurprising that the general characterization of this area of research is that aerobic physical activity behaviors and the resulting attribute of aerobic fitness are beneficial for learning and memory. However, while the acquisition (i.e., encoding) of information is necessary before memories can be retrieved, relatively little work has explicitly assessed whether the rate of learning exhibits similar associations. Some preliminary evidence for such a relationship was provided by Herting and Nagel (2012), who observed that poorer aerobic fitness was associated with a lower rate of spatial memory acquisition across six trials of a virtual Morris Water Maze task in a sample of 30 adolescent children. Alternatively, neither Raine et al. (2013) nor Holzschnieder et al. (2012) observed any such associations between aerobic fitness and the extent to which hippocampal-dependent spatial relational memory was successfully encoded into memory in samples constituting 48 preadolescent children, bifurcated into higher and lower fit groups, and 33 middle-aged adults across a range of aerobic fitness levels. However, given the relatively small samples used by the extant literature—and the predominant focus of these investigations upon whether information was ultimately encoded into memory rather than whether the *rate* of encoding differed—further research is necessary to better examine the associations between aerobic fitness and the rate of acquisition of spatial relational information. In addition, these investigations examined samples of preadolescent children and middle-aged adults—so it is important to also examine healthy young adults to better understand this relationship between fitness and spatial relational memory acquisition across the lifespan. Accordingly, utilizing a well-powered hierarchical regression approach, the association between aerobic fitness and the acquisition of spatial relational memory was assessed in a sample of college-aged young adults using a spatial configuration task. Given a broad body of evidence demonstrating an association between aerobic fitness and the integrity of neural systems involved in supporting relational memory and one study suggesting that fitness might also

impact spatial relational memory encoding (Herting & Nagel, 2012), it was hypothesized that individuals with poorer aerobic fitness would manifest with a slower rate of spatial relational acquisition.

Method

Participants

The analyses were conducted on a sample of 152 college-aged young adults attending Michigan State University. All participants provided written informed consent in accordance with the institutional review board at Michigan State University and reported being free of any neurological disorders, psychological conditions, previous history of head trauma, cardiovascular disease, or physical disabilities, and indicated normal or corrected-to-normal vision. Upon completion of the experimental session, the participants were compensated with extra credit. The demographic and fitness data for all participants are provided in Table 1.

Procedure

Using a cross-sectional design, the participants visited the laboratory on a single day and were instructed not to engage in exercise on the day prior to their scheduled testing session. Upon arrival, the participants provided informed consent and completed both a health history and demographics questionnaire and the Physical Activity Readiness Questionnaire (Thomas, Reading, & Shephard, 1992) to screen for any existing health issues that might be exacerbated by performing the aerobic fitness assessment. The participants were then fitted with a wireless heart rate monitor and had their height, weight, and body composition measured using a stadiometer and a digital Omron HBF-510 Body Composition Monitor and Scale (Omron Healthcare, Inc., Lake Forest, IL), respectively. The Omron scale demonstrates both high reliability ($R_{xx} = .933-.993$) and validity ($r = .942$) for the measurement of body composition in healthy adults (Vasold, Parks, Phelan, Pontifex, & Pivarnik, 2019).

Table 1 Participant Demographic and Aerobic Fitness Characteristics

Measure	All participants	Range
<i>N</i>	152 (115 female)	
Age (years)	19.1 ± 1.2	18–25
Education (years)	13.1 ± 1.2	12–17
Non-White (%)	28%	
Percentage of body fat (%)	29.6 ± 8.0	12.0–54.3
BMI	23.7 ± 3.5	18.3–39.8
Heart rate during spatial configuration task (beats·min ⁻¹)	91.1 ± 15.1	56–125
Maximum heart rate (beats·min ⁻¹)	193.1 ± 11.2	151–232
Maximum RPE	8.1 ± 1.4	4–10
VO ₂ max (ml·kg ⁻¹ ·min ⁻¹)	42.7 ± 9.5	20.0–70.2
VO ₂ max percentile	49.4 ± 34.0	3–97
Trials to memory acquisition	37.4 ± 19.1	8–61
Proportion achieving memory acquisition	71%	

Note. Values are presented as $M \pm SD$. VO₂max percentile based on normative values for VO₂max (Shvartz & Reibold, 1990). BMI = body mass index; RPE = rating of perceived exertion; VO₂max = maximal oxygen consumption.

Following these measurements, the participants were seated in a sound-attenuated testing chamber and were oriented to a spatial configuration task of relational memory using an introductory video (https://youtu.be/4gjRgqunI_M). The participants' aerobic fitness was assessed using a test of maximal oxygen consumption following the completion of the spatial configuration task to ensure that relational memory acquisition was not altered as a result of the aerobic fitness test (Pontifex et al., 2019).

Spatial Configuration Task

Spatial relational memory was assessed using “The Spatial Configuration Task,” a valid (correlated with the Cognitive Map Formation and Use Tasks; $r = -.414$ and $r = .339$, respectively) and reliable (test–retest reliability $r = .814$) index of spatial relational memory (Burles, 2014; Burles, Slone, & Iaria, 2017). In this task, five geometric shapes (e.g., a tetrahedron [i.e., triangular pyramid], top, torus [i.e., donut shape], cylinder, and an icosphere [i.e., sphere made up of triangles]) were arranged in a pseudorandom order in a pentagonal configuration across a transverse plane in an outer-space-like environment. The participants were shown a set of two of these shapes at a time from a first-person perspective and were asked to indicate which one of the remaining three geometric shapes they were viewing this set from. For example, as depicted in Figure 1, given an arrangement composed of the shapes previously listed, the first-person perspective might show a set of two shapes (the icosphere and tetrahedron) from either

the shape adjacent to the set (the cylinder or top) or the shape orthogonal to the set (the torus). The viewing position of each set of two shapes occurred with equal probability from the remaining three shapes (two adjacent and one orthogonal). After each response, the participant watched as the camera rotated to a different geometric shape in the arrangement. The participants were then shown a different set of two shapes and again were asked to indicate from which of the remaining three shapes they were viewing. The participants were never explicitly shown the pentagonal configuration nor provided any relational information other than what was provided through the rotation of the viewing perspective. The task consisted of 60 trials with no time limit, and all participants completed all 60 trials. In order to correctly indicate the viewing position, the participant must form a cognitive representation of the spatial configuration of the objects. To quantify the trial at which a participant had reliably acquired the spatial locations within relational memory, a threshold approach was used to identify the earliest trial at which a participant could correctly identify their viewing position in six out of seven consecutive trials (71% of the sample achieved this criterion). A sliding seven-trial window was used to determine the point at which this occurred, beginning with the first seven trials of the task and moving one trial at a time (e.g., from Trial 1 to Trial 7, from Trial 2 to Trial 8 . . . from Trial 54 to Trial 60) to encompass the entirety of the 60 trials. The participants who did not successfully achieve this threshold were assigned a score of 61 (one trial beyond the total trials administered).

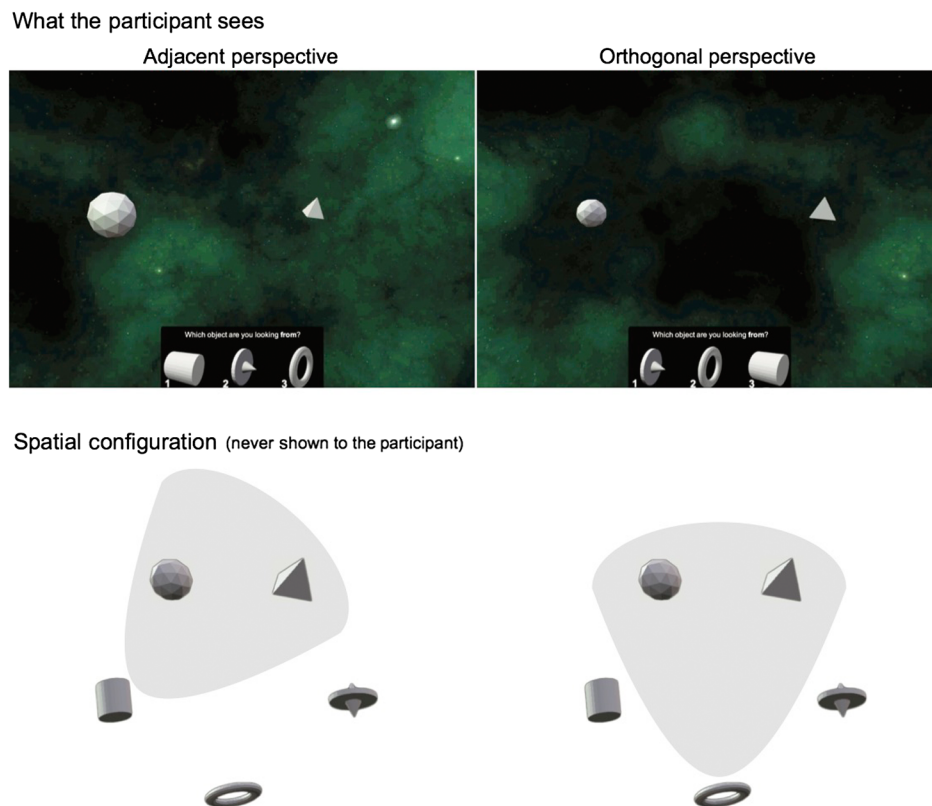


Figure 1 — During the spatial configuration task, participants were shown a set of two shapes at a time from a first-person perspective either adjacent to the set (left) or orthogonal to the set (right) and were asked to indicate from which one of the remaining three geometric shapes they were viewing these objects. The top portion illustrates what participants were shown. The bottom portion illustrates the top-down spatial configuration of the shapes with the viewing perspective denoted by the gray cone. Participants were never shown the top-down spatial configuration of the shapes.

Aerobic Fitness Assessment

To assess aerobic fitness, maximal oxygen consumption (VO_2max) was measured using a computerized indirect calorimetry system (ParvoMedics True Max 2400). Following a brief warm-up period, the participants walked or ran on a motor-driven treadmill at a constant speed, with a 2.5% increase in grade every 2 min until volitional exhaustion (i.e., the participant was no longer able to maintain the exercise intensity). A Polar heart rate monitor (Polar WearLink +31; Polar Electro Oy, Kempele, Finland) provided a continuous measure of heart rate throughout the test, and ratings of perceived exertion values were assessed every 2 min with the OMNI scale (Pfeiffer, Pivarnik, Womack, Reeves, & Malina, 2002). Relative peak oxygen consumption was expressed in milliliters per kilogram per minute and was based on maximal effort as evidenced by attainment of at least two of four confidence criteria: (a) a plateau in oxygen consumption corresponding to an increase of $<2 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ despite an increase in workload, (b) a peak heart rate ≥ 190 bpm, (c) respiratory exchange ratio ≥ 1.1 , and/or (d) ratings on the OMNI scale of perceived exertion >7 (McGowan, Chandler, Brascamp, & Pontifex, 2019; Pontifex, Hillman, & Polich, 2009). The aerobic fitness percentiles were extracted from the normative data from Shvartz and Reibold (1990) to account for differences in oxygen consumption driven by both age and biological sex.

Statistical Analysis

Prior to the analysis, all variables were screened for homoscedasticity and normality. Given the nonnormal distribution of the number of trials necessary for spatial relational memory acquisition, bivariate correlation analyses were conducted using Spearman's rank-order correlation coefficients between demographic factors and the trial at which the acquisition of the spatial relations between objects was achieved. Statistical summaries of the correlational analysis are provided in Table 2. To address the question of whether the attribute of aerobic fitness related to the speed at which individuals acquired spatial relational information within memory, a hierarchical linear regression was performed. This method was used to determine the independent contribution of aerobic fitness (as assessed using VO_2max percentile) for explaining variance in the rate of spatial relational memory acquisition after accounting for statistically significant descriptive factors (i.e., age, biological sex [0 = female, 1 = male], years of education, race [0 = White, 1 =

non-White], and percentage of body fat; Pontifex et al., 2014, 2016). Additionally, using a similar approach, hierarchical logistic regression was performed to address the question of whether the attribute of aerobic fitness related to actually acquiring spatial relational information within memory (regardless of the speed). The outcome variables were either 0 (reflecting that the participant did not acquire spatial relational memory) or 1 (reflecting that they did). All data analyses were performed in R (version 3.6; R Core Team, 2013), utilizing a familywise alpha level of $p = .05$. Given a sample size of 152 participants and a beta of 0.20 (i.e., 80% power), the present research design theoretically had sufficient sensitivity to detect the independent contribution of aerobic fitness if it exceeded an effect size of $f^2 = 0.05$ as computed using G*Power (version 3.1.2; Faul, Erdfelder, Lang, & Buchner, 2007).

Results

For both the linear and the logistic regressions, none of the five demographic variables (age, biological sex [0 = female, 1 = male], years of education, race [0 = White, 1 = non-White], and percentage of body fat) explained a statistically significant amount of change in memory performance. As such, the reported results reflect a model with aerobic fitness entered as the sole predictor of performance.

Overall Behavioral Performance

See Figure 2 for the mean behavioral performance (reaction time and response accuracy) within a sliding seven-trial window across the duration of the spatial configuration task.

Rate of Learning

The linear regression analysis indicated no relationship between the attribute of aerobic fitness and the number of trials needed to acquire relational memory, $R^2_{\text{adj}} = .01$, $F(1, 150) = 2.1$, $p = .15$, $f^2 = 0.01$, $B = 0.07$, 95% confidence interval $[-0.02, 0.16]$, $SE B = 0.05$, $\beta = 0.12$ (see Figure 3). Similar findings were observed when using weaker (four of seven trials and five of seven trials) or more stringent (nine of 10 trials) threshold criteria ($ps \geq .2$), when restricting the analysis to only those participants who acquired the spatial locations within relational memory using these various threshold criteria ($ps \geq .3$), and when using nonlinear models ($ps \geq .1$).

Table 2 Bivariate Correlations Between Demographic Factors, Aerobic Fitness (VO_2max Percentile), and the Number of Trials Necessary for Memory Acquisition of the Spatial Configuration Task

Variable	Age	Sex (0 = female, 1 = male)	Education	Race (0 = White, 1 = non-White)	BMI	Percentage of fat	Aerobic fitness
Sex	.15						
Education	.77**	.07					
Race	-.06	.02	-.06				
BMI	.05	.33**	.11	.08			
Percentage of fat	-.05	-.64**	.04	.09	.37**		
Aerobic fitness	-.02	.26**	-.05	-.26**	-.13	-.47**	
Trials to memory acquisition	-.08	-.11	-.10	.15	-.10	.04	.12

Note. BMI = body mass index; VO_2max = maximal oxygen consumption.

*Correlation was significant at $p \leq .05$. **Correlation was significant at $p \leq .001$.

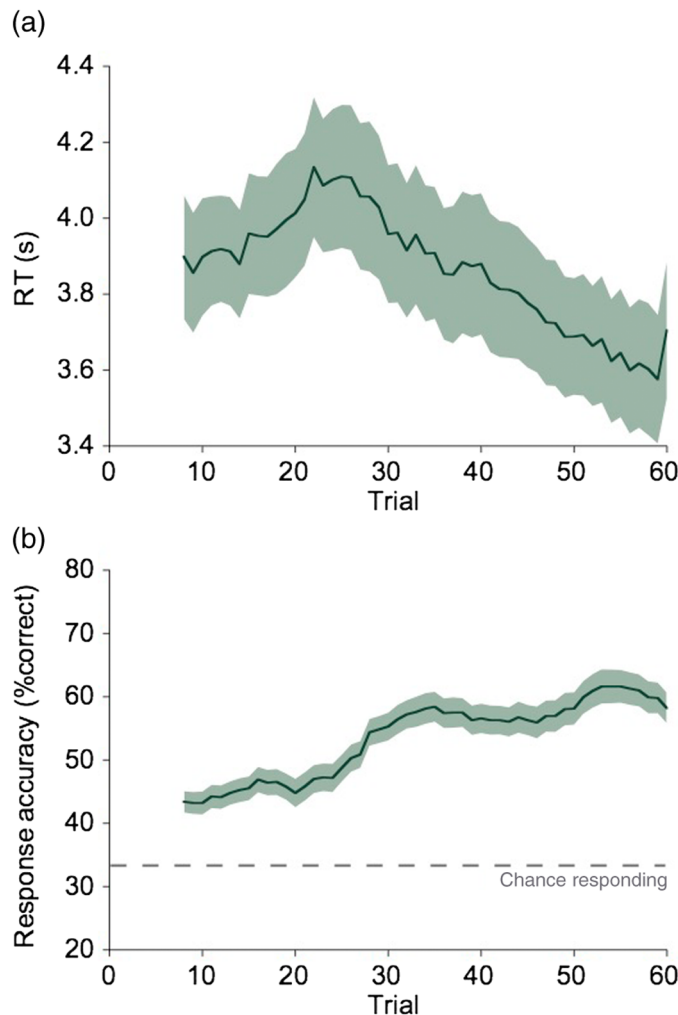


Figure 2 — Illustration of the mean ($\pm SE$) behavioral performance for (a) RT, regardless of correctness, and (b) response accuracy within a sliding seven-trial window across the duration of the spatial configuration task. RT = reaction time.

Attainment of Memory

Logistic regression analysis indicated no relationship between the attribute of aerobic fitness and the likelihood of successfully acquiring relational memory, $R^2_{\text{pseudo}} = .02$, $\chi^2(1, 150) = 2.7$, $p = .1$, $f^2 = 0.01$, $B = -0.01$, 95% confidence interval, $[-0.02, 0.00]$, $SE B = 0.01$, odds ratio = 0.99 (see Figure 3). Similar findings were observed when using weaker (four of seven trials and five of seven trials) or more stringent (nine of 10 trials) threshold criteria ($ps \geq .3$) and when using nonlinear models ($ps \geq .1$).

Discussion

The aim of the present investigation was to determine the association between aerobic fitness and the acquisition of spatial relational learning in a sample of cognitively normal, college-aged young adults. In contrast to our a priori hypothesis that poorer aerobic fitness would be associated with a slower rate of learning, there was no association between aerobic fitness and the speed of encoding. Indeed, even when using less stringent or more stringent criteria for quantifying when memory encoding was achieved,

when restricting the analysis to only those individuals who successfully encoded the spatial locations within relational memory, and when using logistic regression to examine the likelihood of acquiring memory, no relationship with aerobic fitness was observed. Interestingly, consistent with the findings of both Raine et al. (2013) and Holzschneider et al. (2012), lower aerobically fit individuals did not exhibit any difference relative to higher aerobically fit individuals in their likelihood of acquiring the spatial locations within relational memory by the end of the task. Accordingly, aerobic fitness appears to be associated with neither the rate at which college-aged individuals learn spatial-relational information nor the extent to which they ultimately are able to successfully encode such information within memory.

Despite the strength of the present investigation, these findings do not necessarily rule out the possibility of an association between aerobic fitness and the speed of encoding of spatial relational memory. Rather, they suggest that, if such an association were to exist in a sample of cognitively normal young adults, it likely exhibits an exceptionally small effect, given the observed effect size of $f^2 = 0.01$, and would require sample sizes exceeding 800 participants (assuming 80% power) to be detected. Although the present findings stand in contrast to those of Herting and Nagel (2012), it is also important to note that their sample consisted of adolescent children, as opposed to college-aged young adults. Thus, it may be that the influence of aerobic fitness is only able to manifest in populations with impaired or not yet fully developed cognitive reserves, such as elderly adults or preadolescent children (Hayes, Hayes, Williams, Liu, & Verfaellie, 2017; Hillman et al., 2008). Support for such speculation is mitigated, however, given prior work demonstrating associations between aerobic fitness and the retrieval of spatial and nonspatial relational memory in high-functioning college-aged adults (Pontifex et al., 2014, 2016), as well as the present finding that aerobic fitness was unrelated to the likelihood of successfully encoding spatial relational memories—replicating the findings observed in both preadolescent children and middle-aged adults (Holzschneider et al., 2012; Raine et al., 2013). However, further research is needed to better understand the extent to which the speed of encoding spatial-relational information relates to aerobic fitness across the lifespan. The initial acquisition of information involves a molecular process called long-term potentiation, which refers to a series of chemical and physical changes that occur in the brain as connections between synapses are formed (Abel & Lattal, 2001; Loprinzi, Edwards, & Frith, 2017; Nakazawa, McHugh, Wilson, & Tonegawa, 2004). Understanding the factors that alter the speed of encoding is essential, as the rate and strength of long-term potentiation is related to how effectively a memory is consolidated into—and ultimately, retrieved from—long-term memory (Loprinzi, 2019; Nakazawa et al., 2004). Accordingly, further research is necessary to better understand not only how aerobic fitness relates to memory retrieval across the lifespan, but also how processes such as memory encoding and the consolidation of information into long-term memory are associated.

It is also important to acknowledge the cross-sectional nature of the present investigation. While randomized controlled trials have demonstrated that physical activity interventions designed to enhance aerobic fitness are effective at enhancing the retrieval of relational memories and inducing alterations in the neural systems underlying such functions (Erickson et al., 2011; Monti et al., 2012), we have little insight into the extent to which the findings observed within the present investigation differ in response to longitudinal physical activity interventions. Accordingly, further

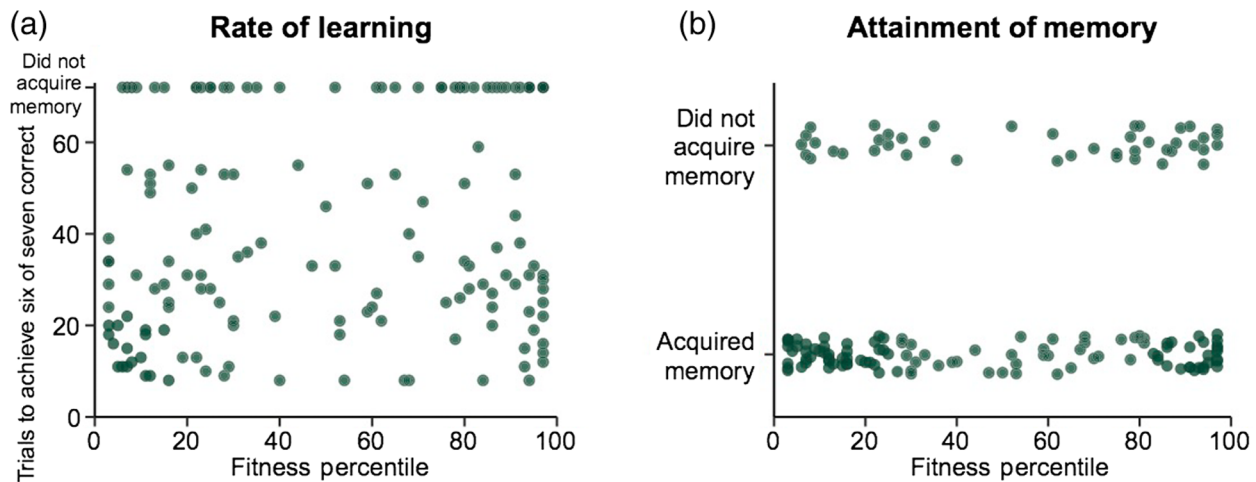


Figure 3 — Scatterplots of the relationship between aerobic fitness and (a) the number of trials necessary for memory acquisition of the spatial configuration task and (b) whether or not relational memory was ultimately acquired.

research is necessary to examine whether such interventions might induce alterations in the acquisition of relational memory encoding. Similarly, it is important to note that the present investigation did not assess more temporally adjacent physical activity behaviors (i.e., physical activity over the 7- to 14-day period prior to memory acquisition); thus, future research should examine the extent to which physical activity behaviors (and the specific types of behaviors), as well as physical health-related attributes such as aerobic fitness, interact and exert mediating/moderating influences upon the distinct aspects of memory.

Collectively, the findings from this investigation provide initial evidence from a well-powered investigation that aerobic fitness does not appear to relate to the rate—nor the extent—of acquisition of spatial relational memory in college-aged adults. Such findings are particularly intriguing, given the neural-system-based frameworks of relational memory that suggest that the encoding of relational memory is dependent upon the hippocampus, whereas memory retrieval is dependent upon the integration of multiple neural systems across the prefrontal and parietal cortices and the hippocampus (Herting & Nagel, 2012). Accordingly, although nonhuman animal findings highlight the influence of aerobic physical activities, particularly upon the hippocampus, in human models, longitudinal aerobic physical activity interventions and cross-sectional investigations of aerobic fitness have demonstrated effects across prefrontal and parietal regions of the brain (Colcombe et al., 2004; Hillman et al., 2008; Voss et al., 2010, 2011). Thus, speculatively, given the present findings that aerobic fitness was not associated with the encoding of spatial relational memory, it may be that the influence of aerobic-based physical activity and the attribute of aerobic fitness act upon the hippocampus in a manner that strengthens the integration of these prefrontal, parietal, and hippocampal networks to facilitate the retrieval of relational information. Taken together, it would appear that the general characterization that aerobic fitness is beneficial for learning and memory may lack sufficient specificity. Rather, given the present findings and the extant literature in this area, it would appear that a more precise statement is that the health-related attribute of aerobic fitness is associated with the retrieval of information from memory. Nonetheless, further research is necessary to examine whether the encoding of information into other types of memory is similarly unrelated to aerobic fitness.

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