Self-reported Physical Activity and Objective Aerobic Fitness: Differential Associations with Gray Matter Density in Healthy Aging

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Self-reported physical activity and objective aerobic fitness: differential associations with gray matter density in healthy aging

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Aerobic fitness (AF) and self-reported physical activity (srPA) do not represent the same construct. However, many exercise and brain aging studies interchangeably use AF and srPA measures, which may be problematic with regards to how these metrics are associated with brain outcomes, such as morphology. If AF and PA measures captured the same phenomena, regional brain volumes associated with these measures should directly overlap. This study employed the general linear model to examine the differential association between objectively-measured AF (treadmill assessment) and srPA (questionnaire) with gray matter density (GMd) in 29 cognitively unimpaired community-dwelling older adults using voxel based morphometry. The results show significant regional variance in terms of GMd when comparing AF and srPA as predictors. Higher AF was associated with greater GMd in the cerebellum only, while srPA displayed positive associations with GMd in occipito-temporal, left perisylvian, and frontal regions after correcting for age. Importantly, only AF level, and not srPA, modified the relationship between age and GMd, such that higher levels of AF were associated with increased GMd in older age, while decreased GMd was seen in those with lower AF as a function of age. These results support existing literature suggesting that both AF and PA exert beneficial effects on GMd, but only AF served as a buffer against age-related GMd loss. Furthermore, these results highlight the need for use of objective PA measurement and comparability of tools across studies, since results vary dependent upon the measures used and whether these are objective or subjective in nature.

Keywords: physical activity, aerobic fitness, voxel based morphometry, healthy aging, MRI, gray matter density

INTRODUCTION

A strong link has been established between higher physical activity (PA) levels and improved cognitive function in aging. Epidemiological studies have found that higher midlife PA is associated with lower risk of cognitive decline and dementia later in life (Hamer and Chida, 2009; Sofi et al., 2011), while exercise intervention studies have identified changes in brain structure and function that are related to improved cognition in the elderly (for a review, see Hayes et al., 2013). Mechanisms by which exercise affects cognitive function in humans include cell proliferation and increased synaptic density (Pereira et al., 2007), angiogenesis (Swain et al., 2003), changes in mitochondrial function (Steib et al., 2014), and alteration of trophic factor signaling, which in turn affects neuronal function and structure in areas that are critical for cognitive function (Phillips et al., 2014). One such example are exercise-induced increases in gene expression of brain derived neurotrophic factor (BDNF), which is critical for learning and memory formation by providing a propitious environment for neuroplasticity. Moreover, exercise has been shown to confer vascular, immunological, and anti-inflammatory benefits as well as changes in brain function, connectivity and perfusion (for reviews of the literature, see Voss et al., 2011; Brown et al., 2013; Erickson et al., 2013; Hayes et al., 2013; Phillips et al., 2014; Svenson et al., 2014). Importantly, changes in brain volume have been identified as a potential mediator (Weinstein et al., 2012) by which exercise affects cognitive function in older adults. Humans display decreased cognitive function and reductions in brain volume as they age, which are most pronounced in prefrontal, temporal, and parietal gray matter (Good et al., 2001; Tisserand et al., 2004; Raz and Rodrigue, 2006) and are ameliorated by exercise (Colcombe et al., 2003, 2006; Bugg and Head, 2011; Erickson et al., 2011;
and AF indeed represent overlapping, but somewhat different
the case for all studies (Honea et al., 2009). Similarly, if PA
somewhat overlapping results (Hayes et al., 2013), this is not
constructs, associations between brain health and tools measuring
these different constructs should differ.
Hence, the current study investigated the relationship between
an objective AF measure (distance traveled on a 12 min treadmill
test) and a self-report PA questionnaire (modified version of the
Leisure Time Exercise Questionnaire) with GMd in cognitively
normal community-dwelling older adults. We hypothesized that
GMd associations would differ respective of AF level as compared
to self-reported PA (srPA) given the nature of the different
constructs and the objective and subjective nature of the indices,
respectively. We also investigated whether AF or srPA modified
the relationship between GMd and age and hypothesized that
AF rather than srPA would modify this relationship given the
objective, and thus more precise nature of this measure compared
to srPA.

MATERIALS AND METHODS
PARTICIPANTS
Thirty cognitively healthy community-dwelling older adults
participated in a study of aging and AF, srPA, functional MRI
(fMRI), and structural MRI. fMRI findings for category fluency
and finger tapping tasks related to aging and srPA have been
reported elsewhere (McGregor et al., 2011; Zlatar et al., 2013).
One participant was excluded from the current analyses due to
evidence of ischemic event on MRI scan, thus 29 structural MRI
scans were included in the current analyses. Participants were
between the ages of 60 and 85 (mean = 68.38, SD = 5.99) and
recruitment took place from flyers, advertisements, and ongoing
aging research registries at the University of Florida in Gainesville.
Years of education ranged between 12 and 20 (mean = 16.14,
SD = 2.36). All participants were right-handed, native English
speakers, who were deemed eligible for MRI scanning following
an extensive screening protocol (e.g., no cardiac pacemaker,
ferrous metal implants, or claustrophobia). Participants were
free of a history of diagnosable neurological conditions (i.e.,
stroke, Alzheimer’s disease, Parkinson’s disease, mild cognitive
impairment), history of head trauma with loss of consciousness,
cardiac conditions, learning disabilities, attention deficit disorder,
history of alcohol or drug abuse (for at least 6 months prior to
participation), and psychiatric conditions. Older adults currently
prescribed beta-blockers for hypertension management were not
included in the study. All subjects obtained Mini-Mental State
Examination (MMSE) scores ≥27 (Folstein et al., 1975) and
scores on a comprehensive neuropsychological battery of tests
were all within the average range of cognitive function, indicating
no apparent global cognitive impairment at the time of testing.
Cognitive testing took place during the 1st study session which
was conducted 1 week prior to brain scanning (refer to Table 1
for a list of tests administered and corresponding scores). Signed
informed consent was obtained from all participants according to
guidelines established by the Health Science Center’s Institutional
Review Board at the University of Florida. Participants were
compensated for their participation in the study.

AEROBIC FITNESS MEASUREMENT
A modified Cooper AF test was conducted (Cooper, 1968)
in which participants were asked to cover as much ground
Table 1 | Participant characteristics and neuropsychological testing scores \( (N = 29) \).

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age</td>
<td>68.4</td>
<td>6.0</td>
</tr>
<tr>
<td>Education (years)</td>
<td>16.1</td>
<td>2.4</td>
</tr>
<tr>
<td>Physical activity (minutes per week)</td>
<td>242.9</td>
<td>204.8</td>
</tr>
<tr>
<td>Aerobic fitness (km)</td>
<td>0.89</td>
<td>0.34</td>
</tr>
<tr>
<td>Hopkins verbal learning test trial: 1 (T score)</td>
<td>46.1</td>
<td>9.9</td>
</tr>
<tr>
<td>Hopkins verbal learning test total trials 1–3 (T score)</td>
<td>49.8</td>
<td>9.9</td>
</tr>
<tr>
<td>Hopkins verbal learning test delayed free recall (T score)</td>
<td>50.3</td>
<td>10.8</td>
</tr>
<tr>
<td>Hopkins verbal learning test delayed retention (T score)</td>
<td>50.9</td>
<td>15.4</td>
</tr>
<tr>
<td>Stroop color word reading (scaled score)</td>
<td>14.5</td>
<td>3.2</td>
</tr>
<tr>
<td>Trail making test part A (scaled score)</td>
<td>8.5</td>
<td>1.8</td>
</tr>
<tr>
<td>Trail making test part B (scaled score)</td>
<td>9.6</td>
<td>1.9</td>
</tr>
<tr>
<td>WAIS digit symbol (scaled score)</td>
<td>10.9</td>
<td>2.3</td>
</tr>
<tr>
<td>WAIS letter number sequencing (scaled score)</td>
<td>11.9</td>
<td>2.3</td>
</tr>
<tr>
<td>WAIS prorated working memory index (standard score)</td>
<td>108.1</td>
<td>11.8</td>
</tr>
<tr>
<td>Controlled oral word association test, letters FAS (scaled score)</td>
<td>10.3</td>
<td>2.1</td>
</tr>
<tr>
<td>Animal verbal fluency (scaled score)</td>
<td>10.3</td>
<td>2.5</td>
</tr>
</tbody>
</table>

Notes: WAIS = Wechsler Adult Intelligence Scale, SD = Standard Deviation.

As possible by walking, jogging, or running on a treadmill for 12 min. The Cooper test is indicated as correlating with VO\(_{2\text{max}}\), with a demonstrated correlation coefficient of 0.92 when comparing it to a treadmill VO\(_{2\text{max}}\) test (Grant et al., 1995). Thus, distance traveled in 12 min (self-paced, variable speed) was used as the main AF variable for the current study. Twenty-nine participants completed the AF assessment with distance between 0.31 to 1.63 km covered in 12 min (mean = 0.89 km, SD = 0.34 km).

**SELF-REPORTED PHYSICAL ACTIVITY MEASUREMENT**

To measure self-reported PA level, a modified version of the Leisure-Time Exercise Questionnaire (LTEQ) was used, which is a 3-item scale that asks participants to rate how often they engaged in mild, moderate, and strenuous leisure-time exercise in a certain period of time (Godin and Shephard, 1985; Godin et al., 1986). The LTEQ is a reliable and valid measure of leisure-time PA behavior in adults (Jacobs et al., 1993) that allows for calculation of total number of minutes spent in light, moderate, and strenuous PA. In the present study, the total number of minutes spent in moderate and strenuous PA in one week was summed and used as the srPA variable. Twenty-nine participants completed the LTEQ questionnaire. The total amount of self-reported time spent performing moderate and strenuous PA ranged between 0 and 900 min in one week (mean = 242.86, SD = 204.78).

**STRUCTURAL BRAIN IMAGING PARAMETERS**

Structural MRI scans for all participants were acquired on a three Tesla Achieva whole-body scanner (Philips), with an 8-channel SENSE radio frequency head coil, at the McKnight Brain Institute of the University of Florida. Structural TFE T1-weighted images were acquired for 160 × 1 mm sagittal slices (FOV = 240 mm; TE = 3.685 ms; TR = 8.057 ms; FA = 8 degrees; matrix = 256 × 256, voxel size = 1.0 mm × 0.938 mm × 0.938 mm).

**PROCEDURE**

An MRI screen was conducted via telephone to identify potential study candidates. Those who were MRI-eligible were asked to obtain written clearance from their primary care physician in order to participate in the treadmill test. The 12 min treadmill test took place during the 1st study session during which neuropsychological assessment was also conducted. Heart rate was monitored throughout the treadmill assessment. Prior to commencing the test, participants were asked to take some time to familiarize themselves with the treadmill and the test began once they reported verbally to the study staff that they were comfortable. After the treadmill test, participants were instructed on how to answer the modified LTEQ, which they completed daily for 7 days following the 1st study session. Structural brain imaging scans were obtained during the 2nd session following the 7 day srPA monitoring period.

**BRAIN IMAGE PROCESSING AND STATISTICAL ANALYSES**

MRI structural images were analyzed using FSL-VBM, a voxel-based morphometry (VBM) analysis (Ashburner and Friston, 2000; Good et al., 2001), carried out with FMRIB Software Library (FSL; Oxford, UK) version 4.1 tools (Smith et al., 2004). This technique allows for the identification of different types of brain tissue (i.e., gray matter, white matter, and cerebrospinal fluid or CSF) at the voxel level by calculating the probability that each voxel contains a particular tissue-type. Pre-processing of the structural images for VBM analysis consisted of the following steps: (a) removing the skull and other non-brain tissue from the structural images using fslnvbm_1_bet (Smith, 2002); (b) performing tissue-type segmentation to generate partial gray matter volumes for each participant in the native space using FAST4 (Zhang et al., 2001); and (c) aligning the resulting gray matter partial volumes to MNI152 2 mm standard space using the non-linear registration tool FNIRT (Andersson et al., 2007a,b), which uses a b-spline representation of the registration warp field (Rueckert et al., 1999). The resulting images were concatenated and averaged to create a study-specific template containing the registered gray matter images for each of the 29 older adult subjects (fslnvbm_2_template-n). All of the gray matter images were then non-linearly registered to the study-specific template (fslnvbm_3_procr). To account for changes in voxel size that occur within the image registration process (expansion and contraction), all registered partial volume images were modulated by dividing by the Jacobian of the warp field (fslnvbm_3_procr). The modulated, segmented images were then smoothed with an isotropic Gaussian kernel of sigma 2 mm, which corresponds to 4.6 mm full-width half-max (FWHM).

We used the randomize option in FSL, which is a permutation-based program allowing for modeling and inference testing using standard general linear model design, when the null distribution of a statistic map is unknown. To describe the unique relationship between GMd, age, fitness level, and srPA,
we conducted two voxel-wise multiple regression models under the
general linear model, higher level/non-time series design
option in FSL: (1) The first regression model used voxel-wise GMd as the
dependent variable and age, AF (distance traveled in 12 min during
treadmill test), and the interaction term between age and AF as
independent variables; and (2) The second regression model included
voxel-wise GMd as the dependent variable and age, srPA (self-reported
minutes of moderate + strenuous activity in 7 days), and the interaction
term between age and srPA as independent variables. These two whole-brain
analyses were conducted using data from all 29 participants,
and the independent variables were centered (demeaned) and
continuous. The resulting probability maps were corrected for
family-wise error ($p < 0.05$) using the Threshold-Free Cluster
Enhancement (TFCE) method. This method enhances cluster-
like regions more than background (noise) by creating output
that is a weighted sum of all of the local clustered signal,
without the need for arbitrary cluster thresholding. If the
voxel-wise analyses returned any significant interaction terms
(age$^*$AF or age$^*$srPA), the average per-subject GMd values were
extracted from significant clusters and further analyzed using
IBM SPSS (version 21) to characterize the direction of the
interaction.

Furthermore, given the reported associations between
GMd and the hippocampus, anterior cingulate cortex, lateral
frontal, and lateral parietal regions (for a recent review, refer
to Hayes et al., 2013), a post hoc region of interest (ROI)
analysis was conducted using anatomically-defined ROIs based on the cortical and subcortical Harvard-Oxford atlases available in FSL. Pearson bivariate correlations were conducted
between mean GMd values extracted from each ROI and
AF and srPA using IBM SPSS. ROIs included: right and left
hippocampi, inferior and middle frontal gyri, frontal pole,
anterior cingulate cortex, and the angular and supramarginal
gyri.

RESULTS

OVERLAP BETWEEN AEROBIC FITNESS AND SELF-REPORTED
PHYSICAL ACTIVITY ON GRAY MATTER DENSITY

Based on the voxel-wise analyses described above, there was no
overlap in regional GMd between the areas significantly associated
with AF and those significantly associated with srPA (Figure 1),
suggesting that AF and srPA are associated with GMd in distinct
and non-overlapping brain regions. The bivariate correlation
between AF and srPA measures was $r = 0.43$, $p = 0.02$.

RELATIONSHIP BETWEEN GRAY MATTER DENSITY AND
SELF-REPORTED PHYSICAL ACTIVITY

Voxel-wise analyses indicated that srPA was significantly
associated with GMd in three discrete clusters after correcting
for age: (1) bilateral occipital poles, lingual and left fusiform
gyri, and right calcarine cortex (occipito-temporal cluster

FIGURE 1 | Results from voxel-wise regression models displaying the
brain regions in which GMd was associated with AF and with srPA after
correcting for age. As can be seen, there was no overlap between GMd in
brain regions associated with AF and those associated with srPA. Areas
where there was a significant association between srPA and GMd included:
(1) bilateral occipital poles, lingual and left fusiform gyri, and right calcarine
cortex (occipito-temporal cluster—BLUE; (2) left central opercular cortex and
middle and superior temporal gyri (left perisylvian cluster—GREEN); and (3)
bilateral frontal poles, superior frontal gyrus, and paracingulate cortex (frontal
cluster—CYAN). There was a significant association between AF and GMd in
the left cerebellum (RED) Clusters are overlaid on the MNI 2 mm brain
template. GMd = Gray matter density. Left = right; Right = left.
depicted in BLUE on **Figure 1**); (2) left central opercular cortex and middle and superior temporal gyri (left perisylvian cluster depicted in GREEN on **Figure 1**); and (3) bilateral frontal poles, superior frontal gyrus, and paracingulate cortex (frontal cluster depicted in CYAN on **Figure 1**). The interaction between srPA and age on GMd was not statistically significant.

**RELATIONSHIP BETWEEN GRAY MATTER DENSITY AND AEROBIC FITNESS**

Voxel-wise analyses indicated that AF was significantly associated with GMd after correcting for age in one cluster located in the left cerebellum (depicted in RED on **Figure 1** after family-wise error correction (TFCE p < 0.05). The interaction term between age and AF was significantly associated with GMd in three clusters: (1) bilateral cerebellum, lingual, and fusiform gyri, and left inferior and middle temporal gyri (temporo-cerebellar cluster depicted in BLUE on **Figure 2**); (2) right superior, middle and inferior temporal gyri, right supramarginal gyrus and planum temporale (right perisylvian cluster depicted in GREEN on **Figure 2**); and (3) left precentral and postcentral gyri (left superior frontal cluster depicted in CYAN on **Figure 2**).

To decompose the interaction term between age and AF on GMd in these significant clusters, a mask of these clusters was created and the averaged GMd for each participant extracted. Hierarchical linear regression models were conducted with the averaged GMd for GMd in these significant clusters, a mask of these clusters was created and the averaged GMd for each participant extracted. GMd in the three significant clusters from the voxel-wise regression were used to assess them. More importantly, AF level associated with AF and srPA levels vary depending on which frontal regions. These results suggest that GMd in brain regions associated with AF and srPA levels vary depending on which measure was used to assess them. More importantly, AF level was a significant moderator of the relationship between age and GMd, while the same was not true of srPA. For those with lower AF levels, there were strong negative associations between age and GMd in left superior frontal and right perisylvian regions suggesting that, as age increases, GMd decreases in this group. To the contrary, individuals with higher AF showed a positive association between GMd and age in temporo-cerebellar regions, indicative of higher GMd in this region as a function of higher age. These results indicate that objectively-measured AF level, but not srPA, may serve as a buffer to delay or reduce age-related decreases in GMd. This is consistent with previous studies showing that cardiorespiratory fitness is associated with sparing of gray matter atrophy in areas that are selectively affected by the aging process (Colcombe et al., 2003). Alternatively, declines in AF may have accelerated age-related GM atrophy; however, whether lower AF causes accelerated atrophy or whether higher AF mitigates age-related GM atrophy cannot be ascertained given the cross-sectional nature of the current study. Future studies that follow both...
Table 2 | Coefficients for the interaction term between age and fitness level on GMd in the three significant clusters from voxel-wise regression.

<table>
<thead>
<tr>
<th>Cluster location</th>
<th>Voxels</th>
<th>COG X, Y, Z</th>
<th>Lower fitness</th>
<th>Higher fitness</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>β t</td>
<td>β t</td>
</tr>
<tr>
<td>Left superior frontal</td>
<td>1146</td>
<td>73.2, 56.2, 49.9</td>
<td>−0.86** −4.04</td>
<td>0.32 1.08</td>
</tr>
<tr>
<td>Right perisylvian</td>
<td>1318</td>
<td>178, 46.9, 39.8</td>
<td>−0.88** −4.12</td>
<td>0.23 0.77</td>
</tr>
<tr>
<td>Temporo-cerebellar</td>
<td>10718</td>
<td>43.8, 32.7, 23</td>
<td>−0.6* −2.65</td>
<td>0.73* 2.3</td>
</tr>
</tbody>
</table>

Notes: GMd = Gray matter density; AF = Aerobic fitness; COG = Center of gravity in MNI 2 mm coordinates; β = standardized beta coefficient; t = t-statistic. Statistically significant coefficient **p < 0.01, *p < 0.05. βs represent the extent and direction of the relationship between age and GMd by AF level for each significant interaction cluster (age*AF on GMd). As can be seen, for those with lower AF, greater age is associated with lower GMd in each of the significant brain regions; whereas greater age is associated with higher GMd in temporo-cerebellar regions for those with higher AF levels.

Figure 3 | Scatter plots depicting individual data points for the three clusters where the interaction term between AF and age on GMd was significant based on the voxel-wise regression model. Table 2 shows the regression coefficients for the moderating effect of AF on age-related GMd changes. AF = Aerobic fitness; GMd = Gray matter density.

fit and unfit individuals over time could help to answer this question.

Although the purpose of the current study was to find voxel-wise associations between AF and srPA with GMd, we conducted post hoc ROI analyses to determine if these two measures were correlated to GMd in brain regions previously identified to be sensitive to exercise and PA in older adults. ROI analyses indicated that there was no association between the objective AF measure and GMd in areas previously shown to be associated with cardiorespiratory fitness such as the hippocampus, anterior cingulate cortex, frontal and parietal regions. This may be due to the fact that we currently used a modified version of the Cooper test, while many other studies have employed VO2max measurement (Colcombe et al., 2003, 2006; Gordon et al., 2008). While AF was not associated to GMd in these ROIs, there was a negative association between srPA and GMd in the left hippocampus, indicating that those with higher self-reported levels of PA had lower GMd in the left hippocampus. Although this seems counter intuitive, it is not surprising given the self-report nature of this measure, which makes it unreliable. Moreover, in the current study, srPA failed to moderate the effects of age on GMd as was the case for the AF measure.

Two factors may affect differences between AF and srPA in their associations with GMd and age. The first is that even though AF and PA are statistically related (as in the current study), they represent different constructs. Hence, it is not surprising that they predict differential brain morphology when the variance for age within this older sample is removed. The second factor is that our measure of AF was objective and our measure of PA was self-report. The lower reliability (and, therefore, greater error variance) of self-report measures may account for the lack modulation of age-related loss in GMd by PA. It is critical to know whether PA can modulate age-related GMd loss. Hence, future studies investigating these associations should rely on objective measurement of PA since srPA is frequently overestimated (Troiano et al., 2008). PA levels can be reliably measured using research-grade accelerometers (Troiano et al., 2008), which provide a summary of time spent in sedentary, light, moderate, and vigorous PA behaviors, allowing for the study of associations between cognitive function and brain health with different PA intensity levels. Given the recent associations between accelerometer-measured sedentary time with brain and physical health in older adults (Gennuso et al., 2013; Zlatar et al., 2014), studying the independent effects of sedentary time on brain and cognitive health will become an important goal for future studies.

The present study is limited by a small sample size and by the fact that the post hoc regression analyses were not conducted by an investigator blinded to the AF data for each participant. Moreover, these results must be interpreted within the context of the current sample, which may not be representative of the general older...
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Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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