Original Article

Physical Activity Predicts Population-Level Age-Related Differences in Frontal White Matter

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Abstract

Physical activity has positive effects on brain health and cognitive function throughout the life span. Thus far, few studies have examined the effects of physical activity on white matter microstructure and psychomotor speed within the same, population-based sample (critical if conclusions are to extend to the wider population). Here, using diffusion tensor imaging and a simple reaction time task within a relatively large population-derived sample (N = 399; 18–87 years) from the Cambridge Centre for Ageing and Neuroscience (Cam-CAN), we demonstrate that physical activity mediates the effect of age on white matter integrity, measured with fractional anisotropy. Higher self-reported daily physical activity was associated with greater preservation of white matter in several frontal tracts, including the genu of corpus callosum, uncinate fasciculus, external capsule, and anterior limb of the internal capsule. We also show that the age-related slowing is mediated by white matter integrity in the genu. Our findings contribute to a growing body of work, suggesting that a physically active lifestyle may protect against age-related structural disconnection and slowing.

Keywords: Brain aging, Exercise, Cognitive decline

Aging is associated with profound changes in brain structure, including gray matter atrophy and alterations in the integrity of white matter (WM). Microstructural changes in the intracellular and extracellular components of WM occur throughout the aging brain, but tend to be more pronounced in frontal associative tracts (1,2). These age-related changes are thought to be driven largely by changes in myelin, with axon fibers being relatively unaffected by age (3). Fractional anisotropy (FA), an index of microstructural WM integrity that is sensitive to changes in cerebral myelin levels, as indexed by postmortem histology (4), declines progressively with age (3,13). The role of WM structures like the genu of corpus callosum in mediating the effect of age on cognitive processing speed has now been replicated many times (2,12), and this relationship appears to be specific to processing speed and executive functioning, rather than other aspects of cognition (eg, language, motor functioning) (10). Thus, maintenance of WM structural connectivity appears to be particularly critical for the prevention of general age-related slowing. However, despite the ubiquity and cognitive relevance of these patterns of change in cerebral WM, the specific mediators explaining these effects—beyond chronological age itself—are unclear.

Although several lifestyle factors probably contribute to the maintenance of WM integrity with age, one of the most robust
predictors of WM health appears to be physical activity. High cardiorespiratory fitness and engagement in physical activity have been shown to have protective effects for WM integrity (14–16) and cognitive performance (17–19) in healthy older adults. Evidence from prospective studies also indicates that physical activity considerably reduces the risk of dementia and Alzheimer’s disease (20). Interestingly, Burzynska and colleagues (21) showed that not only engagement in physical activity, but also avoiding sedentary behavior, is important for preserving WM microstructural integrity later in life, possibly via different pathways. Sedentary lifestyle is more likely to be associated with obesity and poor aerobic fitness, and is a leading cause of disease and disability (22), which, in turn, are shown to be associated with lower WM integrity (23). Longitudinal data from aerobic exercise intervention programs in older adults show that the selective increases in fitness associated with aerobic exercise, but not low-intensity control interventions, predict increases in WM integrity in the prefrontal and temporal cerebrum (24) and increases WM volume in the anterior corpus callosum (25). As noted earlier, these brain regions are particularly vulnerable to the detrimental effects of age. Together, these studies emphasize the potential benefits of physical activity in preventing age-related WM loss.

Although several studies suggest a link between exercise and differences in WM integrity with age (24,26), it remains to be seen whether this relationship holds within a large, population-based life span sample. Population-based samples are critical if our conclusions are to extend beyond relatively select (and potentially biased) samples of research volunteers to the population in general. Moreover, few studies, if any, have examined the relationship between brain health and participants’ reports of everyday activities and routines (encompassing such activities as cleaning the house and mode of transportation/distance to work), which arguably offer a more ecologically valid counterpoint to standard intervention studies (27). In this study, we examined the relationship between age, self-reported physical activity, WM microstructure, and processing speed within a large, population-based sample from the Cambridge Centre for Ageing and Neuroscience (Cam-CAN) (28). Participants (N = 399) completed a physical activity questionnaire (29) and a series of cognitive tests, including simple reaction time (RT) task in their homes, before undergoing a series of structural and functional MRI scans, which included diffusion tensor imaging (28). Diffusion tensor imaging was used to estimate FA within 21 major tracts from the John Hopkins University (JHU) White Matter Atlas and related to physical activity and processing speed separately in a series of mediation models.

Our first objective was to determine whether physical activity mediates age-related decline in WM within particular tracts and whether these are the tracts that are most susceptible to age-related decline. To this end, separate mediation models were run for each tract, testing whether the relationship between age and FA was mediated by daily physical activity. Our second objective was to examine whether performance on the simple RT task is associated with WM integrity and whether the age-related decline in this measure is mediated by WM integrity. Only those tracts that showed a significant mediation effect of physical activity in the first model (corrected for multiple comparisons) were included into the second set of models testing the association between age, FA, and RT. Thus, our planned analyses will help to elucidate a possible explanation for age-related declines in WM health and provide evidence for the role of this measure in predicting declines in processing speed.

Methods

Participants

A healthy, population-based sample of 708 participants (age range 18–88 years) was collected as part of the Cam-CAN (for a detailed description of the study, see ref. (28)). The ethical approval for the study was obtained from the Cambridgeshire 2 (now East of England—Cambridge Central) Research Ethics Committee. Participants gave written informed consent. Exclusion criteria included poor vision (below 20/50 on Snellen test (30)), poor hearing (failing to hear 35 dB at 1,000 Hz in either ear), low Mini–Mental Status Examination (24 or lower (31)), self-reported substance abuse (assessed by the Drug Abuse Screening Test [DAST-20 (32)], poor English knowledge (non-native or nonbilingual English speaker), current psychiatric disorder, or neurological disease. In addition, people with contraindications to MRI or MEG were excluded. Handedness was assessed using Edinburgh Handedness Inventory (33). Of the initial 708, 646 participants had valid T1, T2, and diffusion tensor imaging/diffusion kurtosis imaging data. We also excluded participants who did not complete the RT task (n = 75) and those with outlying FA values further than three times interquartile range above or below the age decile mean (n = 23; total remaining N = 399, 221 females, age range 18–87 years). The sample characteristics are described in Table 1.

Table 1. Participant Demographic Information by Age Decile

<table>
<thead>
<tr>
<th>Age Decile</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>N (percentage of the total 399)</td>
<td>28 (7)</td>
<td>72 (18)</td>
<td>70 (17)</td>
<td>59 (15)</td>
<td>67 (17)</td>
<td>60 (15)</td>
<td>43 (11)</td>
</tr>
<tr>
<td>Age range (y)</td>
<td>18–27</td>
<td>28–37</td>
<td>38–47</td>
<td>48–57</td>
<td>58–67</td>
<td>68–77</td>
<td>78–87</td>
</tr>
<tr>
<td>Sex (male/female)</td>
<td>10/18</td>
<td>35/37</td>
<td>33/37</td>
<td>26/33</td>
<td>29/38</td>
<td>25/35</td>
<td>20/23</td>
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<tr>
<td>Highest education</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>University A’ levels</td>
<td>6</td>
<td>4</td>
<td>8</td>
<td>10</td>
<td>15</td>
<td>13</td>
<td>13</td>
</tr>
<tr>
<td>GCSE grade</td>
<td>3</td>
<td>4</td>
<td>8</td>
<td>8</td>
<td>9</td>
<td>10</td>
<td>7</td>
</tr>
<tr>
<td>None over 16</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>3</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>MMSE</td>
<td>29.18 (1.0)</td>
<td>29.49 (1.0)</td>
<td>28.94 (1.2)</td>
<td>29.05 (1.3)</td>
<td>28.93 (1.3)</td>
<td>28.57 (1.5)</td>
<td>28.02 (1.4)</td>
</tr>
<tr>
<td>Simple RTmean (s)</td>
<td>0.34 (0.04)</td>
<td>0.34 (0.04)</td>
<td>0.35 (0.06)</td>
<td>0.36 (0.06)</td>
<td>0.38 (0.06)</td>
<td>0.40 (0.08)</td>
<td>0.41 (0.07)</td>
</tr>
<tr>
<td>PAEE</td>
<td>43 (13)</td>
<td>46 (16)</td>
<td>52 (16)</td>
<td>47 (17)</td>
<td>38 (15)</td>
<td>34 (16)</td>
<td>25 (13)</td>
</tr>
</tbody>
</table>

Note: MMSE = Mini–Mental Status Examination; PAEE = physical activity energy expenditure (kJ/d/kg); simple RTmean = mean RT on the simple RT task. Values in parentheses are SD.
Aging and Physical Activity

Total PAEE, controlled for gender and education, showed a gradual decline with age, $r = -0.37, p_{\text{adj}} < 0.001$ (Figure 1A). This is also shown in the results of the mediation models as path $a$, that is, the direct negative effect of age on total PAEE (Table 2). Work-related activity ($r = -0.52, p_{\text{adj}} < 0.001$) and commuting-related activity ($r = -0.46, p_{\text{adj}} < 0.001$) showed moderate negative correlations with increasing age, but home-related activity showed a very weak correlation ($r = -0.09, p_{\text{adj}} = 0.6$) and leisure time activity no correlation ($r = 0.09, p_{\text{adj}} = 0.9$) with age (Figure 1B). To conclude, leisure- and home-related activities seem to remain stable across the life span, whereas work- and commuting-related activities decline and probably contribute to the decline in total PAEE.

Aging and WM Integrity

The direct effect of age on FA was negative in all of the analyzed tracts, except the posterior limb of internal capsule, which showed
WM Integrity and Speed of Processing

The second mediation analyses tested whether FA (in the tracts related to exercise) mediated the relationship between age and processing speed. As expected, age was associated with slower responding on the simple RT task, \( B = 0.362, CI = 0.273 \) to 0.452, \( SE = 0.047 \) (Table 3, path c). Critically, mean FA in the genu of corpus callosum significantly mediated the effect of age on RT \( \{ab = 0.150, CI = 0.045 \) to 0.251, \( SE = 0.050; \) Table 3, path ab and c). Suggesting that preservation of WM in the genu of corpus callosum is associated with less age-related slowing (Figure 2B). None of the other tracts showed significant mediation or main effects (Table 3, path ab and c). (These effects remain equal when controlling for gender and education, although gender has a direct effect on FA in anterior limb of internal capsule \( \{B = -0.426, SE = 0.096, 95\% CI = -0.616 \) to \(-0.237\}.)

Discussion

This study had two major aims. First, we examined whether physical activity mediates the effects of age on WM integrity. In line with previous work, we found higher physical activity to have positive effects that may protect against the damaging effects of age on FA in anterior WM tracts, namely, the genu of corpus callosum, uncinate fasciculus, anterior limb of internal capsule, and external capsule. The second aim of this study was to examine whether WM integrity within the tracts that benefit from physical activity mediates age-related slowing of processing speed. Of the four tracts tested, only the genu of the corpus callosum mediated a significant portion of the variance between age and RT on a simple motor task.

This is the first study, to our knowledge, to show a relationship between self-reported everyday activities and FA in a population-derived sample. Although our results rely on a cross-sectional sample, and thus cannot relate physical activity to rates of longitudinal change, these results suggest that those who are more physically active in their day-to-day lives also have more youth-like patterns of WM microstructure. This is consistent with previous studies focusing on healthy older individuals, which have linked higher self-reported physical activity to higher WM volume (40) and lesser WM atrophy (15). Objectively measured cardiorespiratory fitness has also been shown to be associated with FA in the cingulum (23) and large portion of the corpus callosum (14) in older adults. A recent study with two large samples of older adults demonstrated that WM tracts between prefrontal regions and medial temporal lobe are particularly associated with cardiorespiratory fitness and that these associations mediate spatial working memory performance (41). In our sample, which covers the whole adult age range from 18 to 87 years, higher everyday physical activity was associated with less age-related loss of WM in several adjacent anterior tracts. Similarly, a recent study showed that higher cardiorespiratory fitness, assessed with the maximum volume of oxygen uptake (peak VO₂), is related to higher FA in several WM tracts in older adults (42). Their study found regional specificity in the sensitivity to cardiorespiratory fitness, including genu of corpus callosum as one of the responsive regions. As with the current results, they showed that not all WM tracts that decline with age are associated with cardiorespiratory fitness.

Overall, physical activity declined with increasing age. This appears to be due largely to a decrease in activity related to work and commuting, whereas home- and leisure-related activities remained relatively stable across the age span. These results are in line with a recent review concluding that in childhood, habituation to active lifestyle, like active travel or outdoor play, are important.

Figure 1. (A) The effect of age on total physical activity energy expenditure (PAEE). (B) The effect of age on PAEE subtypes of home-, work-, leisure-, and commuting-related activities.

a small age-related increase in FA (Table 2, path c). The effect of age on FA was relatively large (standardized \( \beta \)'s < -0.5) in the genu and body of the corpus callosum, fornix, anterior corona radiata, posterior thalamic radiation, sagittal stratum, and tapetum (Figure 2A and C).

Physical Activity and WM Integrity

The first mediation analyses tested whether total PAEE mediated the age–FA relationships. Four tracts showed a mediation effect that survived false discovery rate correction: genu of corpus callosum, anterior limb of internal capsule, external capsule, and uncinate fasciculus (Table 2, path ab, Figure 2A and C). The mediation effects of PAEE on these WM tracts are positive (Table 2, path ab), suggesting that higher physical activity is associated with less age-related WM degeneration (see Figure 2A). (These effects remain equal when controlling for gender and education, although gender has a direct effect on FA in anterior limb of internal capsule \( \{B = -0.426, SE = 0.096, 95\% CI = -0.616 \) to \(-0.237\}.)
contributors to total daily physical activity, whereas in adulthood, life events have the greatest influence on physical activity behavior (43). In the present data, a drop in work-related activity around

Table 2. Mediation Models Testing the Mediation of the Relationship Between Age and White Matter Integrity (Fractional Anisotropy) in Genu of Corpus Callosum, Anterior Limb of Internal Capsule, External Capsule, and Uncinate Fasciculus by Physical Activity Energy Expenditure

<table>
<thead>
<tr>
<th>White Matter Tract</th>
<th>Path a (Age → PAEE)</th>
<th>Path b (PAEE → FA)</th>
<th>Path ab (Mediation Effect)</th>
<th>Path c′ (Residual Age → FA)</th>
<th>Path c (Age → FA)</th>
<th>B (95% CI)</th>
<th>SE</th>
<th>t</th>
<th>p</th>
<th>B (95% CI)</th>
<th>SE</th>
<th>t</th>
<th>p</th>
<th>B (95% CI)</th>
<th>SE</th>
<th>t</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Genu of corpus callosum</td>
<td>−0.382 (−0.474 to −0.291)</td>
<td>0.046 2.4 &gt;0.01</td>
<td>0.037 2.5 0.017</td>
<td>0.092 (0.019 to 0.164)</td>
<td>0.046 8.24 &lt;.001</td>
<td>0.118 (0.014 to 0.221)</td>
<td>0.053 2.23 .033</td>
<td>−0.045 (−0.094 to −0.006)</td>
<td>0.020 2.50 .017</td>
<td>−0.042 (−0.093 to −0.001)</td>
<td>0.022 2.61 .012</td>
<td>−0.048 (−0.099 to −0.005)</td>
<td>0.028 2.34 .028</td>
<td>−0.048 (−0.098 to −0.005)</td>
<td>0.022 2.40 .018</td>
<td>−0.048 (−0.098 to −0.005)</td>
<td>0.028 2.34 .028</td>
</tr>
<tr>
<td>Anterior limb of internal capsule</td>
<td>−0.382 (−0.474 to −0.291)</td>
<td>0.046 2.4 &gt;0.01</td>
<td>0.037 2.5 0.017</td>
<td>0.092 (0.019 to 0.164)</td>
<td>0.046 8.24 &lt;.001</td>
<td>0.118 (0.014 to 0.221)</td>
<td>0.053 2.23 .033</td>
<td>−0.045 (−0.094 to −0.006)</td>
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<td>−0.042 (−0.093 to −0.001)</td>
<td>0.022 2.61 .012</td>
<td>−0.048 (−0.099 to −0.005)</td>
<td>0.028 2.34 .028</td>
<td>−0.048 (−0.098 to −0.005)</td>
<td>0.028 2.34 .028</td>
<td></td>
<td></td>
</tr>
<tr>
<td>External capsule</td>
<td>−0.382 (−0.474 to −0.291)</td>
<td>0.046 2.4 &gt;0.01</td>
<td>0.037 2.5 0.017</td>
<td>0.092 (0.019 to 0.164)</td>
<td>0.046 8.24 &lt;.001</td>
<td>0.118 (0.014 to 0.221)</td>
<td>0.053 2.23 .033</td>
<td>−0.045 (−0.094 to −0.006)</td>
<td>0.020 2.50 .017</td>
<td>−0.042 (−0.093 to −0.001)</td>
<td>0.022 2.61 .012</td>
<td>−0.048 (−0.099 to −0.005)</td>
<td>0.028 2.34 .028</td>
<td>−0.048 (−0.098 to −0.005)</td>
<td>0.028 2.34 .028</td>
<td></td>
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</tr>
<tr>
<td>Uncinate fasciculus</td>
<td>−0.382 (−0.474 to −0.291)</td>
<td>0.046 2.4 &gt;0.01</td>
<td>0.037 2.5 0.017</td>
<td>0.092 (0.019 to 0.164)</td>
<td>0.046 8.24 &lt;.001</td>
<td>0.118 (0.014 to 0.221)</td>
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<td>0.028 2.34 .028</td>
<td>−0.048 (−0.098 to −0.005)</td>
<td>0.028 2.34 .028</td>
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</table>

Notes: B = standardized regression coefficient; CI = confidence interval; FA = fractional anisotropy; PAEE = Physical Activity Energy Expenditure.

*Significant mediation effects (for all effects, significance is denoted by a 95% CI that does not cross zero; false discovery rate corrected p value < .05).

Figure 2. (A) The relationship between white matter integrity (fractional anisotropy [FA]) and age (steeper line) and age controlled for PAEE (gentler line) in genu of corpus callosum (GCC), external capsule (EC), anterior limb of internal capsule (ALIC), and uncinated fasciculus (UNC). FA decreases gradually with age within all of the analyzed white matter tracts: GCC: r = −.731, p < .001; EC: r = −.404, p < .001; ALIC: r = −.218, p < .001; UNC: r = −.192, p < .001. The detrimental effect of age on FA is diminished in all of the analyzed tracts when PAEE is partialled out from age: GCC: r = −.688, p < .001; EC: r = −.348, p < .001; ALIC: r = −.163, p < .001; UNC: r = −.130, p < .001. The results indicate a positive relationship between higher physical activity and age-related differences in white matter microstructure. (B) The relationship between reaction time and age (steeper line) and age controlled for FA in genu of corpus callosum (gentler line). Reaction times become gradually slower with age: r = .362, p < .001. The effect of age on reaction time is diminished when FA in genu of the corpus callosum is partialled out from age: r = .156, p = .002. The results indicate a positive relationship between white matter integrity in anterior corpus callosum and age-related differences in reaction time performance. (C) White matter tract ROIs from JHU FA atlas. Tracts which survive the first stage of mediation analysis (genu, anterior limb of the internal capsule, and the external capsule) are rendered in (left to right) superior axial, sagittal, and oblique views. (D) Schematic representation of the mediation paths. PAEE mediates the effect of age on FA in genu of corpus callosum. (E) FA in genu of corpus callosum mediates the effect of age on reaction time. Full color version is available within the online issue.
60 years of age coincides with the mean retirement age in our sample. Thus, it may be that people whose everyday activity is highly dependent on the activities associated with work show the greatest drop in the total activity compared with those with an active lifestyle outside of working life. Thus, it seems particularly important to promote physical leisure activities among retired older adults, possibly with the help of societal actions.

Age-related slowing of cognitive processing has been proposed to underlie age-related declines within various domains of cognition (44). In the present study, simple RT slowed gradually with increasing age, which is a common finding among various types of age-related effects on speed of processing (45). Age-related slowing in RT was mediated by FA in the genu of corpus callosum, but not in the other tracts that related to physical activity. These findings are in line with an earlier study suggesting that WM deterioration in the anterior part of the corpus callosum may contribute to general age-related slowing (2), though other studies have also related the splenium of corpus callosum and anterior limb of internal capsule (46) and more global WM structure (12,47) to perceptual-motor speed. A recent study also showed that lower whole brain FA is linked to inefficient brain response to cognitive demands of locomotion (48).

We acknowledge that our results do not speak to causality because mediation analyses based on cross-sectional data do not inevitably represent causal relationships between age, physical activity, WM integrity, and RT. Nevertheless, we assume that age, an independent factor in both of the mediation models, cannot be changed by the influence of other factors and, furthermore, that psychomotor speed (RT) is a result of nervous system functioning (WM integrity), rather than the other way round (49). However, the causal interaction between lifestyle factors (eg, physical activity) and brain structure remains unclear: It is well known that environment and behavior, including physical activity, can cause plastic changes in the brain, but at the same time, changes in brain structure and function are known to influence behavior (ie, willingness toward action demanding physical activity). Furthermore, the strength of such inferences, based on self-reported questionnaire data, are necessarily limited. Although the reliability of such questionnaires is high (50), their absolute validity must be validated with more time-intensive vascular measures, such as VO2 uptake and neuroimaging measures of cerebral perfusion. In addition, it is important to note that the Cam-CAN sample represents the population in the United Kingdom, and thus these results may not generalize to a non-Caucasian population.

To conclude, we found that self-reported levels of physical activity mediated age-related WM loss in a number of anterior tracts. Although bearing in mind the limitations of cross-sectional data and a mediation-based approach, our findings complement the evidence from previous work suggesting that a physically active lifestyle may have protective benefits against age-related structural disconnection and cognitive decline. The findings of this study further support public health recommendations about the benefits of leading a physically active lifestyle across the life span, including older adults.

**Supplementary Material**

Supplementary data is available at *The Journals of Gerontology, Series A: Biological Sciences and Medical Sciences* online.

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Conflict of Interest
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.

References