Cortical structures associated with sports participation in children: a population-based study

Abstract

We studied cortical morphology in relation to sports participation and type of sport using a large sample of healthy children (n=911). Sports participation data was collected through a parent-reported questionnaire. Magnetic resonance scans were acquired, and different morphological brain features were quantified. Global volumetric measures were not associated with sports participation. We observed thicker cortex in motor and premotor areas associated with sports participation. In boys, team sports participation, relative to individual sports, was related to thinner cortex in prefrontal brain areas involved in the regulation of behaviors. This study showed a relationship between sports participation and brain maturation.

Keywords

Physical activity, sports, magnetic resonance imaging, cerebral cortex, schoolchildren

Introduction

According to a recent European study of children between 10 and 12 years of age, only 4.6% of girls and 16.8% of boys reach the recommended 60 minutes spent in moderate-to-vigorous physical activity per day (Verloigne et al., 2012). Low levels of physical activity (PA) during childhood may increase the risk of developing chronic diseases (Ortega et al., 2013), and it has even been shown that high levels of PA are needed for optimal brain development and mental health (Berwid & Halperin, 2012; Kamijo et al., 2011; Khan & Hillman, 2014). There is growing evidence to suggest that PA may directly influence the brain at a functional (Chaddock-Heyman et al., 2013; Kamijo et al., 2011; Khan & Hillman, 2014), structural (Chaddock, Erickson, Prakash, Kim, et al., 2010; Herting & Nagel, 2012; Krafft et al., 2014) and cellular level (Vaynman & Gomez-Pinilla, 2006). Sports participation is an important source of PA in children because it occurs regularly, is of high intensity, and usually occurs with a strong social component among children (De Meester, Aelterman, Cardon, De Bourdeaudhuij, & Haerens, 2014; Vella, Cliff, Magee, & Okely, 2014). Regular engagement in sports is about 43% among European children (Santaliestra-Pasías et al., 2013). Most studies on sport participation compare team and individual sports. Although both types of sports entail sociocultural benefits (Nielsen, Hermansen, Bugge, Dencker, & Andersen, 2013), only team sports have demonstrated beneficial consequences to mental health in children, mostly related to social skills (Schumacher Dimech & Seiler, 2011; Vella et al., 2014).

Some estimates suggest brain growth progresses at a rate of 0.4-1.5 mm per year in children (Sowell et al., 2004). Cortical thickness, a measure of cortical structure, decreases with age starting around puberty, despite continued brain growth in general (Sowell et al., 2004). Brain development in children progresses in a localized and regionally-specific manner, with primary areas (i.e., primary motor cortex) developing earlier compared with regions that are involved in more complex and integrative tasks, such as the temporal or frontal lobes (Gogtay et al., 2004). The apparent cortical thinning during childhood likely results from a combination of increases in the myelin coating of fibers in cortical layers (Sowell et al., 2004) and synaptic pruning (Huttenlocher, 1990). Not all regions of the brain show reductions in

thickness as the brain develops; language regions show a cortical thickening, which may suggest a relationship to the fine tuning and mastery of linguistic skills that occur during childhood (Sowell et al., 2004).

Studies in adults offer support for a relationship between exercise and increased cortical gray matter (GM) volume in regions involved in motor control (Erickson, Leckie, & Weinstein, 2014; Jacini et al., 2009). In children, higher cardiorespiratory fitness has been associated with larger structural brain volumes in subcortical regions critical for memory and learning, including the hippocampus (Chaddock, Erickson, Prakash, Kim, et al., 2010; Herting & Nagel, 2012) and basal ganglia (Chaddock, Erickson, Prakash, VanPatter, et al., 2010). Larger volumes in the dorsal striatum of the basal ganglia were associated with a greater ability to inhibit distraction during a compatible congruent and incongruent flanker task (Chaddock, Erickson, Prakash, VanPatter, et al., 2010). In addition, bilateral putamen and globus pallidus volumes predicted flanker performance in a longitudinal study (Chaddock et al., 2012). Aerobic fitness during childhood also influences the structure of cortical systems, as found in older adults, which may play a role in cognition and school performance (Chaddock-Heyman et al., 2015). Chaddock et al. (Chaddock-Heyman et al., 2015) found that physically fit children (>70th percentile VO_2 max), compared to less-fit children (<30th percentile VO_2 max), showed decreased gray matter thickness in the superior frontal cortex, superior temporal areas, and lateral occipital cortex, which was coupled with better mathematics achievement. Furthermore, the authors showed that cortical gray matter thinning in anterior and superior frontal areas was associated with superior arithmetic performance. There is no evidence regarding the brain areas involved in team sports participation. However, the cooperation with teammates that usually takes place in team sports requires higher cognitive complexity, in comparison to individual sports. This suggests that prefrontal areas may be more developed in children enrolled in team sports, since the cognitive skills acquired during sports participation transfer to cognitive performance
(Best, 2010).

The study performed by Chaddock et al. (Chaddock-Heyman et al., 2015) used aerobic fitness as a proxy indicator of regular PA, however regular childhood PA is rarely intensive and lengthy enough to enhance aerobic fitness, and therefore the relationship between PA and fitness may not be meaningful (Armstrong, Tomkinson, & Ekelund, 2011). Therefore, it is unclear whether differences in cortical thickness are related to PA habits, specifically participation in sports, in children. The advantages of team sports over individual sports already demonstrated with mental health have yet to be explored with brain structure. Moreover, there is a lack of evidence in large population-based samples, which is necessary for applying the findings to the general population. Lastly, studies that employ whole-brain analyses are needed in order to identify other brain areas that may be related to sports participation in children (Chaddock-Heyman et al., 2015). The present study is the first to explore whether extracurricular sports participation is associated with cortical thickness in a large sample of children using whole-brain analyses. This study is also the first to compare cortical thickness between children participating in team vs. individual sports. We focused on extracurricular sports participation because we were interested in comparing children with different levels of sports participation, and curricular sports are similar among children.

This knowledge would be of utmost importance, as childhood is a key period for brain maturation, and extracurricular sports participation could play a crucial role in the development of relevant brain regions. Understanding the potential of sports participation for maximizing brain development of children has significant implications for educators and policy makers who aim to determine strategies and interventions that promote success across lifespan. We used global brain measures and cortical thickness of 6- to 10-year-old children from a population-based cohort to examine whether sports participation was related to brain maturation. Our specific aims were: 1) to study cortical structures related to extracurricular sports participation, and 2) to explore cortical differences associated with type of sport (team vs. individual). Based on studies in adults, we expected to find increased cortical thickness in regions involved in motor control associated with sports participation. Regarding the comparison between team and individual sports, we expected to find thinner prefrontal cortices in children enrolled in team

sports compared to individual sports, since they are exposed situations that require higher-order to cognitive skills.

Methods

Participants

This study was embedded in a population-based cohort investigating children's development from fetal life onward. Sports information was obtained from 6,229 6-year-old children. The neuroimaging wave included 1,070 children aged 6-to-10 years who were scanned between September 2009 and July 2013. A total of 52 children were excluded because of poor image quality, and 107 for missing information on sports participation. Thus, the final study sample consisted of 911 six- to ten-year-old children. After a complete description of the study was provided to the families, written informed consent and assent were obtained from the parents and children, respectively. All procedures were approved by the Ethics Committee of the research center.

Sports participation

Information about usual extracurricular sports participation during an average week was obtained through a parent-reported questionnaire administered when the child was 6 years old (Supplementary Fig. 1). The following activities reported by parents were not treated as regular sports: chess, theater, music, school swimming lessons, and skiing. School swimming lessons were excluded because we focused on extracurricular sports participation in this study. Skiing was excluded because in the region where the study was carried out it is unlikely this sport could be practiced regularly. Finally, the sports were also considered null if parents explicitly reported that the child had stopped practicing the sport when the questionnaire was completed (e.g., "dance until last month"), since these activities were not usual when the questionnaire was filled in.

Using the questionnaire data, we created a continuous score of sports participation based on the information of all reported sports. First, we assigned a value for each category of the variables

"frequency" and "duration", as follows: 1 "1 time per week", 2 "2 times per week", 3 "3 times per week", 4 "More than 3 times per week" for frequency, and 25 "Less than 30 minutes", 50 "30 to 60 minutes", and 75 "More than 1 hour" for duration. These variables were combined to estimate weekly sports participation (in hours) by using the following formula:

$$\begin{aligned} &weekly\ sports\ participation \\ &= \{[(times\ per\ week\ sport\ 1) * (minutes\ sport\ 1)] \\ &+ [(times\ per\ week\ sport\ 2) * (minutes\ sport\ 2)] \\ &+ [(times\ per\ week\ sport\ 3) * (minutes\ sport\ 3)]\}/60 \end{aligned}$$

We also defined two groups of children, those who only participated in team sports (soccer, hockey or basketball), and those who only participated in individual sports (martial arts, dance, gymnastics, tennis, swimming, horseback riding or athletics) (Supplementary Table 1). A high number of children were excluded from the analyses as they were not enrolled in extracurricular sports (n=493). In addition, uncommon sports, such as handball or baseball, defined as less than 0.5% of participation in the total sample with sports data (n=6,229), and combined sports, based on the participation in both team and individual sports or in a unique activity that mixes exercises from different type sports, were excluded in these analyses in order to have more homogeneous groups (n=60). Girls (n=183) were excluded in the analyses comparing team and individual sports due to a small number of girl participants in team sports (n=11). The final sample was 70 boys enrolled in team sports, and 105 boys enrolled in individual sports.

Structural MRI

MR images were acquired using a GE Discovery MR750 3.0 T scanner (GE Healthcare Worldwide, USA) with an eight-channel head coil. The high resolution T1-weighted image was collected using an inversion recovery fast spoiled gradient recalled sequence with the following parameters: TR (repetition time) =10.3 ms, TE (echo time) =4.2 ms, TI (inversion time) =350 ms, NEX (number of excitations) =1,

142 flip angle =16°, readout bandwidth=20.8 kHz, matrix 256 ×256, imaging acceleration factor of 2, and an
143 isotropic resolution of 0.9×0.9×0.9mm^3.

144 *Image quality*

145 We performed image quality assurance in two steps. First, the raw T1 images were rated on a five point
146 Likert scale by trained raters. Scans that were poor (n=50) or unusable (n=1) were excluded at the first
147 quality assurance level. The next step of quality assurance took place after the images were processed
148 through the FreeSurfer pipeline, and consisted of a visual inspection of the segmentation quality of the
149 data. One scan was excluded because the reconstruction failed. Subsequently, the ratings of both levels
150 were compared and ratings that were discrepant between both levels underwent a third rating in which a
151 consensus of the quality of the FreeSurfer segmented image was determined.

152 *Image processing*

153 Cortical reconstruction and volumetric segmentation were performed with the FreeSurfer image analysis
154 suite (http://surfer.nmr.mgh.harvard.edu/) version 5.1. The technical details of these procedures are
155 described in a prior publication (Dale, Fischl, & Sereno, 1999). Cortical thickness was calculated as the
156 closest distance from the grey/white boundary to the grey/cerebrospinal fluid boundary at each vertex on
157 the tessellated surface. The surface-based map was smoothed using a 10mm full-width half-maximum
158 Gaussian kernel prior to whole-brain, surface-based analyses.

159 *Covariates*

160 The covariates specified in the following were considered potential confounders, based on prior literature.
161 Information on gender was obtained from hospital registries. Age was collected when the child was
162 scanned. Maternal education level and ethnicity were included in the study and were assessed through
163 questionnaires. Maternal education was categorized in three levels: no/primary education, secondary
164 education and higher education. Children with both parents born in the local country were considered
165 'local', children with both parents born in Europe (Turkey excluded), North America, Australia, and
New

Zealand were assigned an 'other-Western' ethnic background, and children with at least one parent born in a non-Western country were assigned a 'non-Western' ethnic background. All parents were asked to complete the CBCL 1.5–5 (Achenbach TM & Rescorla LA, 2000) when the participants were 5-6 years old, a self-administered parent-report questionnaire to measure the degree of children's problem behavior.

During the assessment wave at 6 years of age, children's weight and height were measured at the research center using standardized procedures and devices. BMI was calculated as [weight(kg)]/ [height(m)]^2. The intelligence quotient (IQ) of the child was assessed using a shortened version of the Snijders-Oomen Niet-verbale intelligentie Test – Revisie (SON-R 2.5–7), which is a non-verbal intelligence test suited for children of 2.5–7 years of age (Tellegen PJ, Winkel M, Wijnberg-Williams B, & Laros JA, 2005).

Statistical analyses

Differences between boys and girls and between team and individual sport groups were evaluated using Fisher's exact test for categorical variables, and Wilcoxon rank-sum test for continuous variables. Additionally, we performed pairwise tests to compare the average predicted probability of being girl across the categories of sports participation: "no participation", "less than 1 hour/week", and "more than 1 hour/week". We performed pairwise tests adjusted for multiple comparisons using Tukey's honestly significant difference to compare sports participation means across maternal education levels and ethnicities.

We used linear regression models to assess the relationship between sports participation and the following global brain volumetric measures: total brain volume, total gray and white matter volume, and subcortical gray matter volume. Associations between sports participation and each of the global brain measures were assessed in models adjusted for age and gender (partially adjusted model), and in models additionally adjusted for maternal education and child ethnicity (fully adjusted model).

We used cortical thickness as a measure of cortical morphology, which has been proven to be sensitive to neurodevelopmental changes. To investigate the relationship between sports participation and cortical

thickness, we performed vertex-wise analyses, a surface-based approach, using the FreeSurfer QDEC module (Query, Design, Estimate, Contrast), which performs intersubject/group averaging and inference using the general linear model on vertex-wide morphometric data produced by the FreeSurfer processing stream. Analyses were corrected for multiple comparisons using the built-in Monte Carlo simulation at a cluster-wise corrected p value threshold of <0.05.

We performed analyses of covariance (ANCOVA) in QDEC with sports participation as the continuous predictor, gender as a discrete factor, and age as a nuisance variable within the different offset, different slope design matrix. We exported thickness data for each participant for the identified clusters into STATA 12 (Stata Corporation, College Station, Texas) to assess whether the associations withstood correction for additional confounding factors using adjusted linear regression models. We also performed two sensitivity analyses. We excluded left-handed individuals (n=91) in the first sensitivity analysis, and we excluded imaging data that were listed as having fair quality in the second (n=110).

We performed ANCOVA only in boys using QDEC including the sport type (i.e., team or individual sports) variable as a discrete factor and age as a nuisance variable. We explored interactions between age and type of sport in QDEC. Again, we exported thickness data for each participant for the identified clusters into STATA 12. Linear regression models were performed including an interaction between age and individual/team sport.

Results

Sample characteristics

Table 1 shows the characteristics of the study population. Approximately 46% of the children participated in sports regularly. The sports participation pattern was different between boys and girls ($p<0.0001$). At the 5% level, the average predicted probabilities of being girl were significantly different across all categories of sports participation. Compared to children who did not participate in sports, children participating in sports less than 1 hour/week were more likely to be girl, while children participating more

than 1 hour/week were more likely to be boy compared to children participating less than 1 hour/week or not participating in sports. The average of sports participation was different by ethnicity, being higher in the local children (mean=0.66, SD=0.89) than in the other-Western (mean=0.63, SD=0.79) and the non-Western children (mean=0.46, SD=0.75). The differences between local and non-Western children were statistically significant (p=0.01). There were also differences in the time spent in sports by maternal education level; children of mothers with higher education spent an average of 0.67 h/week (SD=0.80) participating in extracurricular sports, while children of mothers with medium education level spent 0.56 h/week (SD=0.93) and children of mothers with primary or low education level spent 0.24 h/week (SD=0.69) playing sports. The comparison between high and low education levels was statistically significant ($p<0.05$). Socio-demographic variables were equivalent in team and individual sports, however boys in team sports spent more time in sport activities ($p<0.0001$) and had a lower IQ ($p<0.05$) (Supplementary Table 2).

Global measures

We found positive associations between total brain volume and total GM volume and sports participation (all $p<0.05$) in partially adjusted models; however, when we adjusted for maternal education and child ethnicity in addition to age and gender, the results were no longer significant (Supplementary Table 3).

Sports participation

After correcting for multiple testing, the association between sports participation and cortical thickness revealed one significant cluster in the left precentral gyrus (size=1590.76 mm^2, number of vertices within cluster=3603, cluster-wise $p<0.001$, Talairach coordinates x=-30.0, y=-9.5, z=47.6) (Fig. 1). This cluster included portions of the superior and caudal middle frontal cortices. We found the thickness of this cluster to be positively associated with sports participation. The association between cortical thickness of this cluster and sports participation remained in the regression model adjusted for age, gender and maternal education (B=0.03; 95%CI=0.02, 0.05). The inclusion of the variables child ethnicity, IQ, and CBCL total problem score did not change the effect estimate (B) meaningfully (≤5%).

The sensitivity analysis excluding 110 fair quality scans (n=801) did not change the results. A more significant association was observed in left precentral gyrus (size=1691.99 mm^2, number of vertices within cluster=3856, cluster-wise p=0.0001, Talairach coordinates x=-30.6, y=-9.3, z=47.9) when only right-handed children were included in the QDEC analysis (n=820) (Supplementary Fig. 2).

Type of sport

We explored thickness differences between team and individual sports in boys, given the unbalanced distribution in girls. We observed two significant clusters in the right hemisphere related to type of sport after correcting for multiple testing (Fig. 2). The first cluster included portions of the superior, medial orbital and rostral middle frontal cortices (size=1770.81 mm^2, number of vertices within cluster=2665, cluster-wise $p<0.001$, Talairach coordinates x=5.5, y=42.5, z=-18.8). The second cluster included portions of the pars triangularis, orbitalis, opercularis and caudal middle frontal cortex (size=1490.68 mm^2, number of vertices within cluster=2709, cluster-wise $p<0.05$, Talairach coordinates x=46.8, y=33.4, z=-12.3). We found thinner cortex in boys enrolled in team sports as compared to boys enrolled in individual sports. An interaction between age and type of sport was also detected. The association between cortical thickness and type of sport remained after adjusting for the interaction between age and type of sport, both in cluster 1 (B=1.63; 95%CI=1.03, 2.24), and cluster 2 (B=1.28; 95%CI=0.74, 1.81), with "team sports" as the reference category. The variables sports participation, child ethnicity and IQ were included in the models as potential confounders; however the effect estimates (B) were essentially the same (≤5% change).

Discussion

This study aimed to examine whether sports participation was related to brain maturation. We found associations between sports participation and cortical thickness in a population-based sample of children. We identified a region involving the left precentral gyrus where thickness was positively associated with

sports participation. Additionally, we observed reduced cortical thickness of some regions in the right frontal lobe in male team sports participants when compared to individual sports participants.

The percentage of sports involvement observed in our sample (46%), was close to the general estimate of 43% described in European children (Santaliestra-Pasías et al., 2013). We found that girls spent less time in sports compared to boys, as has also been shown in previous literature (Verloigne et al., 2012). Our findings that mothers with higher education reported higher sports participation of their children has also been shown in the literature (Nielsen et al., 2013).

We found positive associations between sports participation and cortical thickness in premotor areas of the frontal lobe. Physical exercises as well as motor skill learning have both been shown to induce changes in regional brain morphology in adults. This has been demonstrated for various activities, such as moderate aerobic exercise (Gondoh et al., 2009) and learning how to juggle (Draganski et al., 2004). There is also evidence that individuals with highly specialized skills have greater GM volumes in regions related to the skill as compared to individuals without these capabilities. These alterations have been found for professional musicians (Gaser & Schlaug, 2003) and London taxi drivers (Maguire et al., 2000). In children, previous studies have shown that higher physical fitness levels were associated with greater GM volume of the hippocampus (Chaddock, Erickson, Prakash, Kim, et al., 2010; Herting & Nagel, 2012). Brain areas in close proximity to the regions we report here have been associated with PA in previous studies (Erickson et al., 2014; Jacini et al., 2009; Schlaffke et al., 2014). However, the comparison of the findings should be taken with caution, since these studies have been mostly conducted in adults and expert athletes. These regions, part of the medial frontal lobe with dense connections to the primary motor cortex (precentral gyrus), play a key role in motor control, motor skill acquisition, coordination of movements, visual cognition and motor planning (Goble et al., 2010). The supplementary motor area (SMA) is critically involved in coordinating temporal sequences of actions, bimanual coordination, postural stability and internally generated movement (as opposed to stimulus driven) (Goble et al., 2010). The dorsal premotor cortex is thought to play an important role in response selection based

on arbitrary cues and in the control of arm movements. The frontal eye field (FEF) is a cortical area which is part of highly distributed saccadic and visuo-spatial networks with important bearing on the control of eye movements in 3D space and contributing to several aspects of attentional and visual cognition (Vernet, Quentin, Chanes, Mitsumasu, & Valero-Cabré, 2014). This area is especially relevant for soccer players, who have shown improved cognitive functions such as perception and attention compared to non-athletes (Verburgh, Scherder, van Lange, & Oosterlaan, 2014).

In children, cortical thickness normally is reduced as the brain develops (Sowell et al., 2004), however, the areas related to the language skills show an increase in cortical thickness, which has been suggested to be linked to the fine tuning and mastery of linguistic skills that occur during childhood (Sowell et al., 2004). In this study, we interpret the increased cortical thickness in premotor areas as a higher complexity of these regions, involving glial cells, vasculature, and neurons with dendritic and synaptic processes, in children enrolled in sports as compared to children not enrolled in sports. The main neurobiological processes related to PA that could lead to a more complex structure in the brain are: neurogenesis, synaptic plasticity, growth factors and cerebrovascular remodeling (Voss, Carr, Clark, & Weng, 2014). However, the direction of the association cannot be addressed with our data, so the higher structure complexity observed in premotor brain areas could predispose children to sports participation. The increased complexity found in these brain structures at a younger age, either due to sports participation or not, would result in improved capacities in motor skills later in life.

We found that boys enrolled in team sports had thinner cortices in two frontal areas compared with children who only play individual sports. As normative data on maturation of cortical thickness indicated (Sowell et al., 2004), the thinning of these areas may suggest that children participating in team sports have an advantage on the development of these frontal areas, as compared to children enrolled in individual sports. The participation in team sports has been related to psychosocial benefits in previous literature (Schumacher Dimech & Seiler, 2011; Vella et al., 2014). It is worth noting that in our sample higher IQ was observed in children participating in individual sports as compared to children enrolled in

team sports. In line with our results, a previous study found that participation in rowing was associated with a higher cognitive advantage in secondary school boys, as compared to participation in rugby and soccer (Bradley, Keane, & Crawford, 2013). As far as we know, there is no previous literature describing structural brain differences between participants in team and individual sports. The findings observed here suggest that team sports could foster the maturation of specific brain areas involved in regulative ability, with respect to rewards and punishment (Bechara, Damasio, Damasio, & Anderson, 1994), and inhibitory control (Chavan, Mouthon, Draganski, van der Zwaag, & Spierer, 2015) in relation to individual sports. Particularly, two frontal areas were involved, the first region included portions of the superior, medial orbital and rostral middle frontal cortex, and the second region included portions of the pars triangularis, orbitalis, oppercularis and caudal middle frontal cortex. The orbitofrontal cortex has been reported to regulate the planning of behaviors with reward and punishment (Bechara et al., 1994). Middle frontal areas are known to be relevant for realizing motor plans (Cavina-Pratesi et al., 2010; Gallivan, McLean, Flanagan, & Culham, 2013; Gallivan, McLean, Valyear, & Culham, 2013). Finally, pars triangularis, orbitalis and opercularis are related to inhibitory control, a key executive component referring to the ability to suppress cognitive and motor processes (Chavan et al., 2015). Overall, the earlier maturation of the areas involved in behavior regulation, motor planning and inhibitory control could be due to the exposure to higher complex situations in children enrolled in team sports, such as cooperation with teammates, that require higher-order cognitive processes (Best, 2010). Thus, the training of specific cognitive skills during team sports participation may have promoted the maturation of the brain areas involved in these cognitive functions. Conversely, the brain structure may also precede the preference for a specific sport, in other words, the ability of regulating behaviors or teamwork, and the structural characteristics inherent to them, may influence the participation in team or individual sports. Therefore, we were not able to confirm causal relationships based on our results.

Some methodological limitations should be mentioned. Regarding the exposure variable, the children's sports participation was reported by the parents and the data was only an approximation of the real time

spent in sports. In addition, the period when the questionnaires were filled in could influence the response (e.g., during holidays). Regarding the sample, there is a potential selection bias, since children who were excluded differed from the sample on socioeconomic factors and behavioral problem scores. The data for this study was cross-sectional, which precludes inferences about causality. Moreover, there was a time interval between the sports questionnaire and the MRI scan ($\bar{x}$ =1.8, σ=0.9), leading to the possibility that the child gave up the sport during the period between both waves. In order to control the potential effect of different age in the MRI wave, we adjusted the models for age at the scanning session. However, there is evidence in the literature that physical activity tends to be somewhat stable over time (Telama et al., 2014). Since we measured sport activities at 6 years of age the results may not generalize to older children. For example, at 10 years of age children tend to specialize in one sport and play that sport more frequently (Santaliestra-Pasías et al., 2013). The young age of our sample restricted the comparison between team and individual sports, and we were unable to evaluate girls involved in team sports, due to the small sample size of girls participating in team sports. At younger ages, girls tend to play more sports considered "for girls" such as dance than at adolescence, while "neutral" sports such as basketball increase across ages in girls (Viñas-Fort & Pérez-Villalba, 2011). Furthermore, there were some important differences in socio-demographic variables between both groups; however this was expected due to the inherent differences between team and individual sports. Finally, we did not have into account the possible repetitive head impacts, more common in team sports, which may negatively alter children's brain structure. Therefore, the contribution of repetitive head impacts on the cortical thinning observed in team sports participants remained unknown.

This study has a number of strengths. We imaged children from a large population-based, ethnically diverse cohort with information about sports participation and other important confounding factors. This provides the unique opportunity to test differences in brain morphology associated with sports in healthy children drawn from the general population. This is important as the findings can be generalized to the general population of children. The question about sports participation included club sports as well as

362 school-based sports, more easily accessible in terms of location and costs (De Meester et al., 2014;
363 Nielsen et al., 2013). In addition, the detail of the questions allowed us to divide the sample in two
364 types of sports and to study the differences in brain structure between these groups.

365 **Conclusions**

366 This study supports a positive relationship between extracurricular sports participation and the cortical
367 thickness of brain areas associated with motor control. This study also shows evidence for the
368 relationship between team sports participation and the maturation of prefrontal brain areas involved in
369 the regulation of behaviors, motor planning and inhibitory control. Longitudinal studies are needed in
370 order to establish causality, and further explore the effect of team/individual sports on differences in
371 brain development. Future studies including older children are warranted, since sports participation
372 peaks at around 11-13 years of age and the sport practiced at these ages is more specialized, which
373 allows better comparisons between the neural correlates of being involved in team and individual sports.
374 A larger sample of girls is needed to study the associations between team versus individual participation
375 in sports in relation to cortical morphology.

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Supplementary Figure 1. Question about sports participation at 6 years old completed by parents

5. Does your child take part in sports (for example, football, judo, gymnastics, jazz ballet, tennis, etc.)? It is possible that your child plays more than 1 sport. You can fill this in for sport 2 and sport 3*.

- No, go on to question 6

- Yes, namely:

a. Sport 1: ☐

b. How many times per week does your child participate in this sport?

- 1 time per week

- 2 times per week

- 3 times per week

- More than 3 times per week

c. How long, on average, does your child participate in this sport each time (training session or match)?

- Less than 30 minutes

- 30 to 60 minutes

- More than 1 hour

*Continued if necessary for sports 2 and 3

Supplementary Figure 2. Sensitivity analysis. Association between sports participation (hours per week) and cortical thickness in right-handed children aged 6-10 years (n=820). LH = left hemisphere. Colors represent the $-\log^{10}$ (p value). Monte-Carlo Null-Z Simulation was applied to correct for multiple testing ($p<0.05$). The cluster equals a positive relationship between cortical thickness and sports participation, accounting for gender and age.

Table 1. Participant characteristics

	~~Total (n=911)~~	Boys (n=490)	Girls (n=421)
Age brain imaging, years (mean, SD)	~~7.9 (1.0)~~	8.0 (1.0)	7.9 (1.0)
Child ethnicity (%)			
Local	~~70.6~~	72.5	68.4
Other western	~~6.6~~	6.5	6.7
Non-western	~~22.8~~	21.0	24.9
Maternal education (%)			
No/primary	~~3.4~~	3.7	3.1
Secondary	~~41.3~~	42.7	39.7
Higher	~~55.3~~	53.7	57.2
Behavioral problems, CBCL general score (mean, SD) **	~~26.1 (20.7)~~	27.3 (20.6)	24.6 (20.7)
Non-verbal IQ, score (mean, SD)	~~102.3 (14.4)~~	101.6 (15.1)	103.1 (13.5)
BMI index (mean, SD)	~~16.1 (1.6)~~	16.1 (1.6)	16.1 (1.6)
Sports participation, h/week (mean, SD)	~~0.6 (0.9)~~	0.7 (0.9)	0.6 (0.8)
Sports participation (%) ***			
No	~~54.1~~	56.1	51.8
Less than 1h/week	~~26.6~~	20.2	34.0
More than 1h/week	~~19.3~~	23.7	14.3

CBCL = Child Behavior Checklist; IQ = Intelligence Quotient; BMI = Body Mass Index.

***p<0.0001; **p<0.01

Supplementary Table 2. Additional table of participant characteristics (only boys) stratified by type of sport (team vs. individual)

	Team sports (N=70)	**Individual sports (N=105)**
Age brain imaging, years (Mean, SD)	8.07 (1.05)	7.98 (1.01)
Ethnicity (%)		
Local	80.00	74.29
Other western	1.43	7.62
Non-western	18.57	18.10
Maternal education (%)		
Low	1.43	0.95
Medium	38.57	35.24
High	60.00	63.81
Weekly sports participation, hours/week (Mean, SD)***	1.65 (0.84)	1.15 (0.61)
CBCL, score (Mean, SD)	21.80 (17.74)	24.29 (17.91)
IQ, score (Mean, SD)*	100.02 (15.27)	104.78 (14.47)
BMI index (Mean, SD)	16.06 (1.45)	15.94 (1.40)

CBCL = Child Behavior Checklist; IQ = Intelligence Quotient; BMI = Body Mass Index.

***p<0.0001; *p<0.05

Supplementary Table 3. Regression models of sports participation (hours per week) and brain global measures

	Reference[a]	B	95% CI	p	β
Total brain volume, mm^3					
Model 1[b]	916716.1	9571.0	-9.2, 19151.3	0.050	0.06
Model 2[c]	923018.8	5986.7	-3390.6, 15364.0	0.211	0.04
Total gray matter volume, mm^3					
Model 1[b]	593414.6	6396.0	96.7, 12695.4	0.047	0.06
Model 2[c]	598992.1	3824.3	-2303.9, 9952.5	0.221	0.04
Total white matter volume, mm^3					
Model 1[b]	286129.7	2964.5	-525.6, 6454.7	0.096	0.05
Model 2[c]	286498.5	1976.0	-1484.9, 5436.8	0.263	0.03
Subcortical gray matter volume, mm^3					
Model 1[b]	55185.0	-88.3	-444.4, 267.9	0.627	-0.01
Model 2[c]	54860.1	-190.5	-543.8, 162.8	0.290	-0.36

CI = Confidence Interval

[a] reference volume for a boy, 6 years old in model 1, and reference volume for a boy, 6 years old, local and with low maternal education in model 2.

[b] Adjusted for: gender and age.

[c] Additionally adjusted for: ethnicity and maternal education.

Figure 1. Association between sports participation (hours/week) and cortical thickness in children aged 6-10 years (n=911). LH = left hemisphere. Colors represent the $-\log^{10}$ (p value). Monte-Carlo Null-Z Simulation was applied to correct for multiple testing ($p<0.05$). The cluster equals a positive relationship between cortical thickness and sports participation, accounting for gender and age.

Figure 2. Differences in cortical thickness between boys aged 6-10 years performing team vs. individual sports (n=175). RH = right hemisphere. Colors represent the $-\log^{10}$ (p value). Monte-Carlo Null-Z Simulation was applied to correct for multiple testing ($p<0.05$). Numbers refer to the entire clusters. The clusters are thinner in team sports group as compared to individual sports group in boys, accounting for age. We excluded children not performing sport (n=494), children performing both team and individual sports or non-common sports (n=59) and all girls (n=183), as only 11 girls participated in team sports.