PNAS RESEARCH ARTICLE | PSYCHOLOGICAL AND COGNITIVE SCIENCES NEUROSCIENCE

OPEN ACCESS

The effect of learning to drum on behavior and brain function in autistic adolescents

Marie-Stephanie Cahart[a,1], Ali Amad[a,b], Stephen B. Draper[c], Ruth G. Lowry[d], Luigi Marino[c], Cornelia Carey[e], Cedric E. Ginestet[f], Marcus S. Smith[g], and Steven C. R. Williams[a]

Edited by Michael Goldberg, Columbia University, New York, NY; received May 27, 2021; accepted March 17, 2022

This current study aimed to investigate the impact of drum training on behavior and brain function in autistic adolescents with no prior drumming experience. Thirty-six autistic adolescents were recruited and randomly assigned to one of two groups. The drum group received individual drum tuition (two lessons per week over an 8-wk period), while the control group did not. All participants attended a testing session before and after the 8-wk period. Each session included a drumming assessment, an MRI scan, and a parent completing questionnaires relating to the participants' behavioral difficulties. Results showed that improvements in drumming performance were associated with a significant reduction in hyperactivity and inattention difficulties in drummers compared to controls. The fMRI results demonstrated increased functional connectivity in brain areas responsible for inhibitory control, action outcomes monitoring, and self-regulation. In particular, seed-to-voxel analyses revealed an increased functional connectivity in the right inferior frontal gyrus and the right dorsolateral prefrontal cortex. A multivariate pattern analysis demonstrated significant changes in the medial frontal cortex, the left and right paracingulate cortex, the subcallosal cortex, the left frontal pole, the caudate, and the left nucleus accumbens. In conclusion, this study investigates the impact of a drum-based intervention on neural and behavioral outcomes in autistic adolescents. We hope that these findings will inform further research and trials into the potential use of drum-based interventions in benefitting clinical populations with inhibition-related disorders and emotional and behavioral difficulties.

autism | drumming | fMRI | inhibitory control

Significance

There is an acknowledged need for improved service provision in the context of autism spectrum disorders. Previous studies have demonstrated the positive role drum training can play in improving behavioral outcomes for children and adolescents with emotional and behavioral difficulties. However, to date, none of these studies has explored how these behavioral changes translate at the neural level. Our study provides strong evidence that drumming not only reduces hyperactivity and inattention in autistic adolescents but also strengthens functional connectivity in brain regions responsible for inhibitory control and action outcome monitoring.

Autism spectrum disorder (ASD) is a lifelong neurodevelopmental disorder characterized by deficits in social communication and social interactions as well as a range of restricted, repetitive interests, activities, and behaviors (1). Over recent decades, incidence estimates for ASD have increased (2), with a prevalence of 1 in 59 children in the United States (3) and over 600,000 people in the United Kingdom, which is equivalent to a population prevalence of ∼1% (4, 5). In this context of increased autism prevalence, there is an existing need to develop interventions that offer new insights and perspectives and help address the specifically high demand for services for autistic adolescents and young adults (6). [The term "autistic" is used throughout this paper because of a large percentage of the UK autism community's preference for the identity-first construction (e.g., "autistic person") over the person-first phrase (e.g., "person with autism") (7).] Indeed, autistic young people often face discontinuity in care provision in the transitionary period from child and adolescent services to adult services, just when their care needs are most pressing, making their transition into adulthood particularly difficult (8). In particular, mismatches across services, such as differences in eligibility criteria or age cutoffs, mean that many autistic young adults fall through the care gap after exiting high school (8). Autistic individuals are particularly vulnerable during this period because they often face high unemployment rates, increased levels of comorbid psychiatric diagnoses such as anxiety and depression, and, more broadly, greater reliance on assistance from others when it comes to carrying out adulthood-related daily activities (9–11).

A growing body of research suggests that key social domains of the ASD symptomatology may be related to atypical executive functioning (12, 13). Inhibitory control, one of the core executive functions (EFs), corresponds to the ability to delay the onset of behavioral responses, or withhold behaviors that are prepotent but contextually inappropriate (14, 15). It works in concert with other EFs, such as cognitive flexibility and working memory, to exert top-down control on behavioral responses, enable self-regulation, and help navigate social relationships, therefore supporting transition into adulthood and independent living (16, 17). More specifically, it is thought that atypical

Author affiliations: [a]Neuroimaging Department, Kings College London, London SE5 8AF, United Kingdom; [b]Lille Neuroscience & Cognition Department, University of Lille, INSERM U1172, Centre Hospitalier Universitaire Lille, Lille, F-59000 France; [c]Department of Sport, Hartpury University, Gloucester GL19 3BE, United Kingdom; [d]School of Sport, Rehabilitation and Exercise Sciences, University of Essex, Essex CO4 3SQ, United Kingdom; [e]Department of Psychiatry, Royal College of Surgeons, Dublin 2 D02 YN77, Ireland; [f]Department of Biostatistics and Health Informatics, Kings College London, London SE5 8AF, United Kingdom; and [g]Institute of Sport, Nursing and Allied Health, University of Chichester, Chichester PO19 6PE, United Kingdom

Author contributions: M.-S.C., S.B.D., R.G.L., C.C., M.S.S., and S.C.R.W. designed research; M.-S.C., S.B.D., R.G.L., C.C., M.S.S., and S.C.R.W. performed research; M.-S.C., A.A., S.B.D., R.G.L., L.M., and C.E.G. analyzed data; and M.-S.C. wrote the paper.

The authors declare no competing interest.

This article is a PNAS Direct Submission.

[1]To whom correspondence may be addressed. Email: marie-stephanie.cahart@kcl.ac.uk.

Published May 31, 2022.

inhibitory control in autism may underlie significant strengths but may also exacerbate key features of the ASD symptomatology, such as struggling with change and uncertainty, or having difficulty interpreting social cues (18–21). Impaired performance on inhibitory control tasks is frequent in autistic individuals (12, 13, 22, 23). In particular, it has been associated with severe restricted and repetitive behaviors (19, 24, 25), as well as a deficit in proactive response slowing [the ability to slow the initiation of a behavioral response in preparation for stopping during conditions of uncertainty (19)]. At the neuroimaging level, prior studies have revealed atypical recruitment of frontal regions in autistic adolescents (20), and impaired functional connectivity (FC) of the inferior frontal junction, key regions for inhibitory control, in autistic children (26).

Autistic individuals often report being preoccupied with certain topics (27) and struggling with anxiety and anger management (28, 29). In a study by Van Hees et al. (30), higher-education autistic students described feeling overwhelmed by the demands placed on them while facing significant difficulties with planning, information processing, time management, organizational skills, and sensory overload. These difficulties may reflect impaired attention and inhibition abilities, complementary processes that allow individuals to pursue the achievement of a particular goal while remaining flexibly responsive to environmental demands (21, 31). A research study on a population-based twin sample of 17,000 children (9 y to 12 y old) concluded that the vast majority of children with ASD traits also exhibit cooccurring attention deficit and hyperactivity disorder (ADHD) traits (32). More specifically, the authors demonstrated that 82% of the boys and 95% of the girls with high ASD traits on all three ASD domains (social impairments, communication impairments, and restricted repetitive behaviors and interests) exhibited difficulties on at least one of the three ADHD domains (attentional difficulties, hyperactivity, and impulsivity). Additionally, they reported that repetitive and restricted behaviors in ASD correlated with ADHD domains, particularly with impulsivity and attentional difficulties. This is in line with a previous twin study in adults, which reported the highest phenotypic and genetic overlap between ADHD traits and "nonsocial" autistic-like traits such as attention switching difficulties (33).

Music has long been known to promote cognitive and emotional wellbeing in both clinical and healthy populations (34, 35). Rhythm-based musical training, in particular, has been shown to enhance higher-order cognition and motor control (31). There is growing evidence that activities designed to improve beat synchronization skills may provide an effective approach to developing neurological processes that underpin self-regulation and EF skills (36). Indeed, EF deficits have been linked with poor rhythm perception in children (37) and poor sensorimotor synchronization in young adults (38). Using the Integrated Visual and Auditory Plus Continuous Performance Test (39), Slater et al. (31) highlighted that drumming practice is associated with better scores in inhibitory control and selective attention in adult percussionists compared to nonmusicians.

More specifically, learning to drum requires error monitoring and temporal accuracy and therefore both attentional and inhibitory control (31, 40). In a recent study, Lowry et al. (40) used a mixed-methods analysis to investigate behavioral changes in children with emotional and behavioral difficulties, after learning to drum. Following drum training, the participants displayed enhanced attentional focus and reduced hyperactivity and peer problems (40). These results concur with Draper et al.'s (41) recent findings showing that drumming improves motor control and attentional focus and reduces emotional and peer problems in autistic children. It is important to note that motor control is particularly relevant in the context of ASD. Indeed, recent studies have consistently demonstrated motor impairments across the autism spectrum (42, 43), including gross and fine motor difficulties (44, 45) and delays with motor planning (46). Sokhadze et al. (47) showed that ∼80% of autistic individuals also present with clumsiness or motor dyspraxia, which can manifest as having difficulty with motor coordination as well as concentration, planning, and organization. These difficulties may impact the individual's ability to carry out daily activities, which, in turn, can lead to rejection from peers and social isolation (48). Similarly, motor impairments in balance, motor accuracy, and object manipulation scores have been reported to be predictive of social dysfunction in young autistic boys (49). In this context, learning to drum could be regarded as particularly beneficial because it involves not only musicality but also the development of multimodal skills such as body coordination, sensorimotor integration, and cardiovascular exercise processes (50). Additionally, it is appealing and accessible to everyone regardless of age, gender, ethnicity, or musical background (51, 52).

In our proof-of-concept study, Amad et al. (53) showed that the brain is capable of neuroplastic modifications through drum-based practice in neurotypical adolescents. In particular, changes in FC were observed post drum training in brain regions known to exhibit atypical functioning in autism, such as areas associated with motor skills and the mirror neuron system.

In the present study, we investigated the impact of drum training on brain function in 36 autistic adolescents who were split into two age- and gender-matched groups: a drum group (n = 19), who were evaluated before and after learning to drum, and a control group (n = 17), who were also evaluated longitudinally but with no intervention. We explored behavioral outcomes related to drum practice in this clinical population and examined their association with changes in FC between the two groups (i.e., drum group vs. control group) over time (i.e., before vs. after drum training).

We hypothesized that drumming performance would improve in the drum group over time, while no improvement would be observed in the control group. Furthermore, we hypothesized that changes in hyperactivity, attentional difficulties, problem behaviors, and repetitive and restricted behaviors would be observed in the drum group. We also hypothesized that cooccurring changes in FC in brain areas responsible for attentional focus and inhibitory control would be identified following drum training.

Results

Demographic Information. There was no significant difference between groups with regards to participants' age, gender, levels of autism symptoms severity, trait anxiety, sensory difficulties, and IQ at baseline. Results of the independent sample t tests at baseline are provided in Table 1 for the entire dataset (n = 36). All of the participants were right handed, and none of the participants met the criteria for a learning disability.

Drumming Performance. The drumming performance analysis was carried out on a subset of 32 participants. Full details about this subsample are provided in Table 2 and in *Materials and Methods*. An ANOVA showed a significant time*group interaction for the timing error measure ($F_{(1,30)} = 4.678$, $P = 0.039$,

Table 1. Demographic and clinical information, independent sample *t* tests, and associated effect sizes for the entire dataset (n = 36) at baseline

	n	Mean	SD	Independent sample *t* tests	D
Age				$t_{(34)} = 0.901$, $P = 0.374$	0.301
Controls	17	18	1.5		
Drummers	19	17.6	1.3		
Autism symptoms				$t_{(34)} = -0.195$, $P = 0.846$	−0.065
Controls	17	29.24	9.99		
Drummers	19	29.84	8.64		
Trait anxiety				$t_{(34)} = -1.157$, $P = 0.255$	−0.386
Controls	17	44	10.75		
Drummers	19	48.05	10.26		
Sensory sensitivity				$t_{(34)} = -0.395$, $P = 0.695$	−0.132
Controls	17	44.76	3.49		
Drummers	19	45.37	5.37		
IQ				$t_{(34)} = 1.910$, $P = 0.065$	0.638
Controls	17	120.88	12.96		
Drummers	19	112.42	13.54		

D, Cohen's D.

effect size $\eta^2 = 0.14$). Paired *t* tests revealed that the drum group exhibited a significant improvement in relation to timing error over time ($t_{(16)} = 3.547$, $P = 0.003$), while the control group did not ($t_{(14)} = 1.086$, $P = 0.296$; Fig. 1 and Table 3). There was no significant difference between the two groups in terms of drumming performance at baseline. Full details of demographic information as well as statistical results and associated effect sizes for the paired *t* tests are provided in Table 3. Further tests also revealed a very strong correlation between timing error and relative timing error measures ($r = 0.89$, $P < 0.001$). Within this subset of 32 participants, 27 participants exhibited anticipation difficulties at baseline. More specifically, 11 participants in the control group and 16 participants in the drum group obtained negative scores on the relative timing error measure at baseline. Overall, the drum group exhibited a significant improvement in relation to anticipation error over time ($t_{(15)} = -3.009$, $P = 0.009$), while the control group did not ($t_{(10)} = -0.410$, $P = 0.691$). Scatter plots for the timing error and anticipation error measures are provided in Fig. 1.

Psychological Testing.

Social skills. An ANOVA was performed in order to examine whether there was a significant interaction of group over time (time*group) in the context of social skills and problem behaviors. Results revealed a significant time*group interaction for only the hyperactivity/inattention subscale ($F_{(1,34)} = 9.56$, $P = 0.004$; effect size $\eta^2 = 0.22$; Fig. 2).

Paired *t* tests performed within the drum group showed a significant decrease in overall problem behaviors ($t_{(18)} = 3.324$, $P = 0.004$), externalizing ($t_{(18)} = 2.335$, $P = 0.031$), and hyperactivity/inattention ($t_{(18)} = 3.645$, $P = 0.002$) post drum training compared to before. Paired *t* tests within the control group were nonsignificant across all of the subscales.

Full details of demographic information as well as statistical results and associated effect sizes are provided in Tables 1–3.

Significance was set at $P < 0.05$.

Repetitive behaviors. An ANOVA was performed on each of the repetitive behavior measures but did not reveal any significant result.

Table 2. Demographic and clinical information, independent sample *t* tests and associated effect sizes for the subsample (n = 32) at baseline

	n	Mean	SD	Independent sample *t* tests	D
Age				$t_{(30)} = 0.683$, $P = 0.500$	0.242
Controls	15	17.93	1.53		
Drummers	17	17.59	1.33		
Autism symptoms				$t_{(30)} = 0.148$, $P = 0.884$	0.052
Controls	15	30.33	8.15		
Drummers	17	29.88	9.03		
Trait anxiety				$t_{(30)} = -1.712$, $P = 0.097$	−0.607
Controls	15	44.07	9.40		
Drummers	17	49.71	9.20		
Sensory sensitivity				$t_{(30)} = 0.017$, $P = 0.986$	0.006
Controls	15	44.73	3.41		
Drummers	17	44.71	5.24		
IQ				$t_{(30)} = 1.285$, $P = 0.209$	0.455
Controls	15	121	13.83		
Drummers	17	116	7.67		

D, Cohen's D.

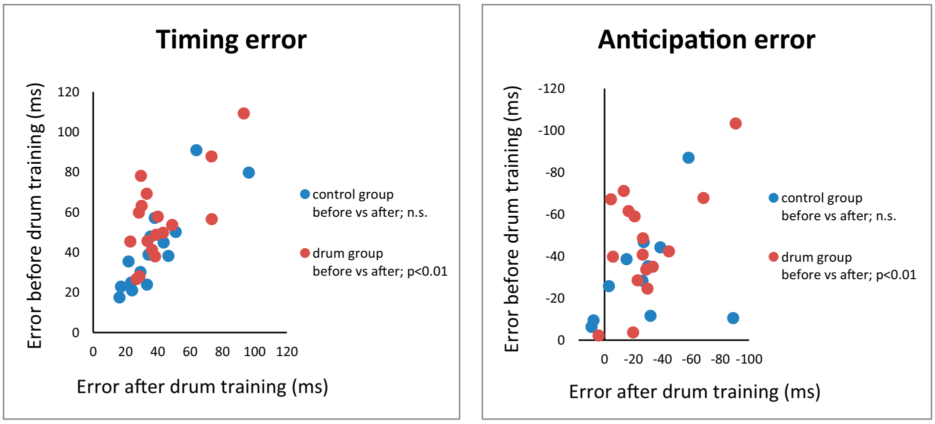

Fig. 1. Timing error (n = 32) and anticipation error (n = 27) before (y axis) and after (x axis) drum training for the control group (in blue) and the drum group (in red). A significant, within-group, reduction in both timing and anticipation errors was observed following drum training, as well as a significant interaction of group over time for the timing error ($F(1,30) = 4.678$, $P = 0.039$); n.s., nonsignificant.

Paired t tests within the drum group revealed a significant reduction in overall repetitive behaviors ($t_{(18)} = 2.527$, $P = 0.021$), stereotyped behaviors ($t_{(18)} = 2.514$, $P = 0.022$), and sameness behaviors ($t_{(18)} = 3.321$, $P = 0.004$) within the drum group. Paired t tests within the control group were nonsignificant across all of the subscales.

Seed-to-Voxel Analyses. The first seed-to-voxel analysis revealed a significant increase in FC after drum training, compared to before, in the drum group compared to the control group (time*group interaction) between the right dorsolateral prefrontal cortex (rDLPFC) and 1) the left frontal pole, the frontal medial cortex, the left paracingulate gyrus, and the right frontal pole, and 2) the left cuneal cortex, the left intracalcarine cortex, the precuneus, the left superior lateral occipital cortex, and the left supracalcarine cortex. A significant increased FC after compared to before drum training within the drum group (paired t test) was also observed between the rDLPFC and the precuneus and posterior cingulate gyrus (see Figs. 3 and 4;see Table 4 for Montreal Neurological Institute [MNI] peak coordinates in the MNI space). No significant change in FC was observed in the control group. Results were thresholded at a voxel-wise $P < 0.001$ and at the cluster extent $P < 0.05$, false discovery rate (FDR) corrected.

The second seed-to-voxel analysis showed significant increased FC after drum training, compared to before, in the drum group compared to the control group (time*group interaction) between the right inferior frontal gyrus (rIFG) and left superior lateral occipital cortex and left superior parietal lobule. A significant increased FC after compared to before drum training was also observed within the drum group (paired t test) between the rIFG and two symmetric clusters of activation: 1) left superior lateral occipital cortex and left superior parietal lobule and 2) right superior lateral occipital cortex and right superior parietal lobule (Figs. 5 *A* and 6 *A* and Table 5). Clusters of increased FC connectivity also exhibited an overlap with the dorsal attention network as illustrated in Figs. 5 *B* and *C* and 6 *B* and *C*. No significant change in FC was observed in the control group.

Voxel-to-Voxel Analysis. The data-driven multivariate pattern analysis (MVPA) using timing error as a regressor revealed four clusters associated with an improvement in drumming performance after drum training, compared to before, in the drum group compared to the control group. These clusters consisted

Table 3. Descriptive statistics, paired *t* tests and associated effect sizes

	n	Mean	SD	SE	Paired t tests	D
TE - controls	15				$t_{(14)} = 1.086$, $P = 0.296$	0.28
Before		41.57	21.36	5.52		
After		38.41	20.77	5.36		
TE - drummers	17				$t_{(16)} = 3.547$, $P = 0.003$	0.86
Before		56.40	21.03	5.10		
After		42.37	19.54	4.74		
AE - controls	11				$t_{(10)} = -0.410$, $P = 0.691$	−0.12
Before		−31.26	23.53	7.50		
After		−27.50	28.61	8.64		
AE - drummers	16				$t_{(15)} = -3.009$, $P = 0.009$	−0.75
Before		−45.59	25.93	6.86		
After		−27.98	23.75	5.94		
H/I - controls	17				$t_{(16)} = -0.884$, $P = 0.390$	−0.21
Before		8.76	3.767	0.91		
After		9.41	4.501	1.09		
H/I - drummers	19				$t_{(18)} = -3.645$, $P = 0.002$	0.84
Before		10	2.887	0.66		
After		7.63	2.872	0.66		

TE, timing error; AE, anticipation error; H/I, hyperactivity/inattention; n, number of participants; D, Cohen's D effect size.

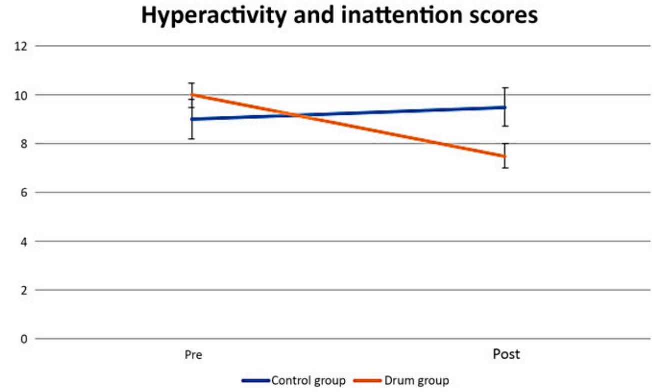

Fig. 2. Hyperactivity and inattention scores (mean and SE) before and after drum training for the control group (n = 17) and the drum group (n = 19). The ANOVA revealed a significant interaction of group (drum group versus control group) over time (after versus before).

of 1) the medial frontal cortex and the left and right paracingulate gyrus; 2) the medial frontal cortex and the subcallosal cortex; 3) the left frontal pole and the frontal medial cortex; and 4) the caudate, the left nucleus accumbens, and the subcallosal cortex (Fig. 7 and Table 6).

Results were thresholded at a voxel-wise $P < 0.001$ and, at the cluster extent $P < 0.05$, FDR corrected.

Discussion

The main goal of this study was to determine whether improvement in drumming performance was associated with changes in behavioral outcomes and FC in autistic adolescents who had undergone drum tuition over 8 wk compared to a control group who had not received any intervention. In line with our first hypothesis, our results showed that the drumming ability of the drum group significantly improved over time, while no change was observed in the control group. More specifically, the improved drumming performance was closely associated with measures of improved anticipation which reflect the enhanced ability to delay the onset of motor responses. Furthermore, we saw a significant reduction in measures of hyperactivity and attentional difficulties in the drumming group compared to controls. These results concur with previous studies on drumming highlighting the role of drumming interventions in reducing hyperactivity in children with emotional and behavioral problems (40) and improving attentional focus in autistic children (41) and adult percussionists (31).

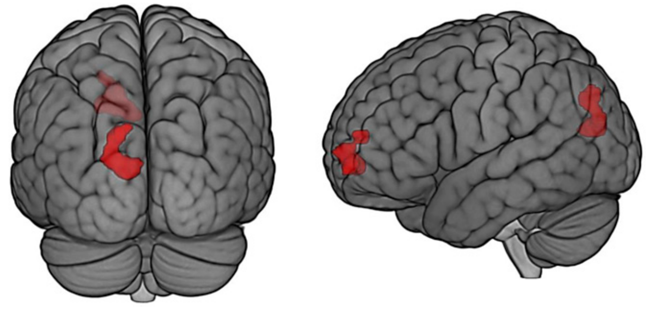

Fig. 3. Results from seed-to-voxel FC analyses of the rDLPFC (n = 36); ANOVA (after > before; drum group > control group). Higher FC was revealed after drum training, compared to before, in the drum group compared to the control group within 1) the left frontal pole, the frontal medial cortex, the left paracingulate gyrus, and the right frontal pole and 2) the left cuneal cortex, the left intracalcarine cortex, the precuneus, the left superior lateral occipital cortex, and the left supracalcarine cortex.

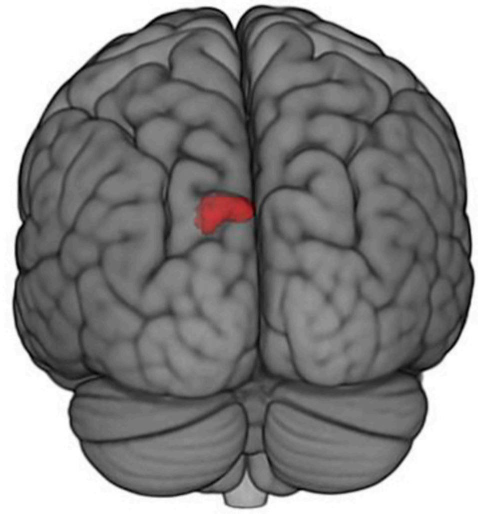

Fig. 4. Results from seed-to-voxel FC analyses of the rDLPFC (n = 36); paired t test within drum group (after > before). Higher FC was revealed after drum training within the precuneus and the posterior cingulate gyrus.

In the present study, a significant reduction in problem behaviors, repetitive behaviors, stereotyped behaviors, and sameness behaviors was also revealed within the drum group following drum training, which suggests an increased ability to manage social relationships, improved cognitive flexibility, and a reduced resistance to change following drum training. A significant improvement in externalizing scores was also observed within the drum group, which emphasizes the role of drum practice in helping release physical tensions in the body and reduce verbal and physical aggression toward peers, a key protective factor for mental well-being (54). These results are in line with Ascenso et al.'s (54) findings showing an enhanced sense of social well-being following drum training. However, the present findings did not reveal any significant changes at the interaction level for problem behaviors, repetitive and stereotyped behaviors, sameness behaviors, and externalizing, which only partially confirmed our hypotheses.

One of the other main results of this study demonstrates a significant increase in FC in two key regions involved in attention and inhibitory control following drum training.

The rDLPFC is one of the main regions of the central executive network. It is known to be involved in attentional control (55, 56) and response inhibition (57), and it has a specific role in multisensory attention (55), which is particularly relevant for drum training. In the present study, the rDLPFC showed an increased FC with the precuneus and the posterior cingulate gyrus, which are central nodes of the default mode network (DMN). It is worth noting that the rDLPFC is part of the so-called task-positive network which is known to be anticorrelated with the DMN, or task-negative network, during the maintenance phase of working memory tasks, and positively coupled during encoding and retrieval phases when the external stimulation is present (58). In the context of resting-state (rs)-MRI studies, atypical FC between the two networks has been identified in various psychiatric disorders such as depression (59) and posttraumatic stress disorder (PTSD) (60). In line with our findings, increased FC between the DLPFC and the posterior cingulate cortex has previously been observed in a study investigating mindfulness training in patients with PTSD (61). In particular, the level of connectivity between the DLPFC and the posterior cingulate cortex following the

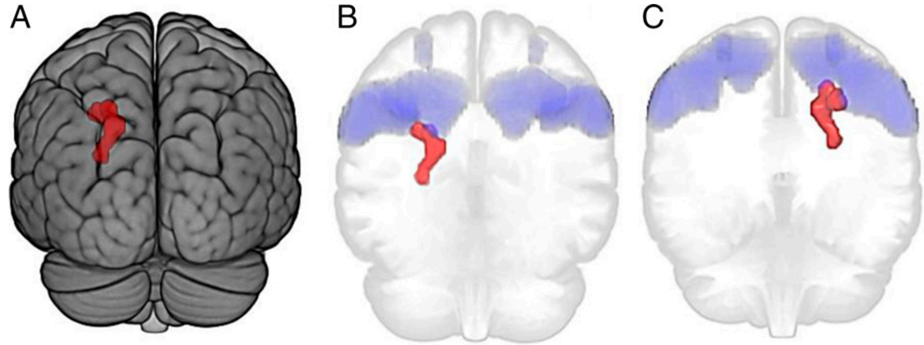

Fig. 5. Results from seed-to-voxel FC analyses of the rIFG (n = 36); ANOVA (after > before; drum group > control group). (*A*) Higher FC was revealed after drum training, compared to before, in the drum group compared to the control group in the left superior lateral occipital cortex and the left superior parietal lobule. (*B* and *C*) The observed cluster of increased FC (red) overlapped with the dorsal attention network (blue). (*B*) The view is from the back. (*C*) The view is from the front.

mindfulness intervention was significantly correlated with improvement in avoidant and hyperarousal PTSD symptoms and was thought to reflect increased capacity for shifting one's attention toward self-awareness, interoceptive processes, and emotional introspection. Interestingly, increased FC between the DMN and task-positive regions has also previously been associated with creative idea production (62). In the context of music, the precuneus has also been found to increase in FC, in music students compared to nonmusic students, with regions involved in interoceptive and emotional processing such as the opercular/
insular regions (63). Taken together, the present findings could reflect the role of the rDLPFC, the precuneus, and the posterior cingulate cortex in self-referential and mentalizing processes, such as the ability to understand the mental states of oneself and others, which are known to be impaired in autistic individuals and are essential for social interactions and musical performance (63, 64). Indeed, in ASD, recruitment of the precuneus has previously been shown to be negatively correlated with Autism Diagnostic Observation Schedule total and social scores (65). In line with these results, Rojas et al. (66) also found a negative correlation between the precuneus gray matter volume and Autism Diagnostic Interview social and communication total score.

Another key finding of this study is the increased FC of the rIFG with the left superior lateral occipital cortex and the left superior parietal lobule after drum training. This is consistent with Amad et al.'s (53) findings which showed a recruitment of the left lateral occipital cortex in healthy individuals following drum training. Indeed, the lateral occipital cortex subserves the functions of visual and haptic object exploration (67) in addition to verbal and nonverbal communication such as face perception (68), mentalizing (69), and language development (70). In ASD, a decreased FC of the lateral occipital cortex has been found to negatively correlate with social communication scores (71), while an out-of-sync intrinsic activity between upper limb motor areas and the lateral occipital has been related to more severe social deficits (72).

In this study, the rIFG seed was also more functionally connected with the superior parietal lobule which has an important role in spatial orientation. More specifically, this cluster of increased FC exhibited an overlap with the dorsal attention network which is known for its key role in externally directed attention (56). Indeed, the superior parietal lobule is part of the dorsal attention network and is known to be involved in modulating spatial attention and maintaining an internal representation of the body in space, and decreased activation of the superior parietal lobule in ASD has been observed in motor learning and response inhibition tasks (73–75). The superior parietal lobule has also been associated with repetitive behaviors and the processing of emotional body posture in ASD (69, 75).

Together with the rIFG and the lateral occipital cortex, the superior parietal lobule has also been involved in action observation and imitation (76–79). Overall, this cluster of strengthened FC may reflect the benefits of music-based motor learning on the integration of body-based senses, which is particularly relevant for mirror responses in relation to action understanding and social interactions in the context of ASD.

The unbiased data-driven MVPA analysis highlighted four main clusters of connectivity associated with drumming performance, three of which are known to closely relate to inhibitory control abilities.

The first cluster was located in the medial frontal cortex and the left and right paracingulate gyrus. These areas have been previously associated with risk behaviors and impulsivity

Table 4. Results from seed-to-voxel FC analyses of the rDLPFC (n = 36)

	Cluster size	Brain areas	MNI coordinates *X*	*y*	*z*	F/T	*P* value
ANOVA (F)						3.37	0.002
	358	Left frontal pole, frontal medial cortex, left paracingulate gyrus, right frontal pole	−04	+56	−06		
	356	Left cuneal cortex, left intracalcarine cortex, precuneus, left superior lateral occipital cortex, left supracalcarine cortex	−10	−78	+14		
Paired *t* test (T)						3.73	0.039
	185	Precuneus, posterior cingulate gyrus	−12	−66	+28		

ANOVA (after > before; drum group > control group) and paired *t* test (after > before within the drum group). MNI coordinates (*x, y, z*) represent peaks within a cluster. Cluster size corresponds to spatial extent (i.e., number of voxels). Correction for multiple comparisons was performed using FDR correction at the cluster level.

Table 5. Results from seed-to-voxel FC analyses of the rIFG (n = 36)

	Cluster size	Brain areas	MNI coordinates *X*	*y*	*z*	F/T	*P* value
ANOVA (F)						4.37	0.016
	307	Left superior lateral occipital cortex, left superior parietal lobule	−18	−62	+42		
Paired *t* test (T)						5.73	0.003
	320	Left superior lateral occipital cortex, left superior parietal lobule	24	−64	+44		
	189	Right superior lateral occipital cortex, right superior parietal lobule	+30	−56	+40		

For the rDLPFC: the paired *t* test within drum group (after > before). For the rIFG: ANOVA (after > before; drum group > control group). MNI coordinates (*x, y, z*) represent peaks within a cluster. Cluster size corresponds to spatial extent (i.e., number of voxels). Correction for multiple comparisons was performed using FDR correction at the cluster level.

tendencies in the context of adolescents with high-risk behavioral tendencies (80) and during tasks involving delayed and risky choice in adult gamblers and drug users (81).

The second cluster also comprised the medial frontal cortex in addition to the subcallosal cortex. These brain regions are known for their involvement in decision-making and affective processes, especially the social understanding of the self and others, and the regulation and inhibition of emotional responses (82, 83). This result aligns with prior studies demonstrating the medial frontal cortex's involvement in motor impulsivity (84), impulsive aggression (82), and attention-related impulsivity, both in healthy controls (85) and in illicit substance–dependent individuals (86). The medial frontal cortex has also been shown to be involved in facial affect recognition in ASD (87) and self–other representation in the context of compensatory camouflaging in autistic women (88, 89).

The third cluster was located in the frontal pole and the frontal medial cortex, in the left orbitofrontal cortex. The frontal pole is involved in monitoring action outcomes, which includes the ability to anticipate consequences to one's actions, evaluate whether implemented strategies are effective, and generate alternative strategies to issues that may arise (90). These abilities contribute to enhanced cognitive flexibility and self-monitoring, which are an important determinant of social outcomes and transition into adulthood (91). This cluster is also known for its involvement in action restraint and action cancellation mechanisms in the context of go/no-go and stop signal tasks (92).

Finally, the fourth cluster comprised the caudate, the left nucleus accumbens, and the subcallosal cortex, key nodes of the reward system. The nucleus accumbens, in particular, has long been known to be involved in the anticipation of monetary and social reward in healthy adolescents and adults (86, 93). Of special relevance here is that previous research has shown increased activity in the caudate in the context of synchronous drumming as well as monetary reward tasks within the same group of participants, suggesting a link between interpersonal synchrony and the reward system (94). More specifically, autistic individuals have been shown to exhibit lower striatal reactivity to both social and monetary rewards compared to healthy controls (95). Indeed, it is thought that atypical reward mechanisms might affect the consolidation of positive memories of social experiences, thus leading to decreased motivation for social engagement and increased salience of nonsocial events.

Clinical Implications. From a clinical perspective, our results show that drumming practice improves brain function and behavioral outcomes in clinical populations with social communication difficulties and repetitive, restricted behaviors and activities such as ASD. They also demonstrate that drumming interventions could be particularly interesting to consider in disorders involving attentional difficulties and inhibitory control issues such as ADHD, dyspraxia, dementia, and traumatic brain injury. Additionally, drum training could also benefit other populations with emotional and behavioral difficulties such as depression, eating disorders, and PTSDs, because of its key role in facilitating the integration of body-based senses and offering a nonverbal means of self-expression.

Limitations. One of the limitations of this study is its relatively small sample size, especially given the heterogeneity in the phenotypic presentation of ASD. It is worth noting that, despite a small sample size, the improvements in timing error and hyperactivity/inattention in the drummers were associated with large effect sizes in the paired t tests (Cohen's D = 0.86 and 0.84, respectively) and large effect sizes in the ANOVAs ($\eta^2 = 0.14$ and 0.22, respectively). Additionally, an independent sample t test revealed

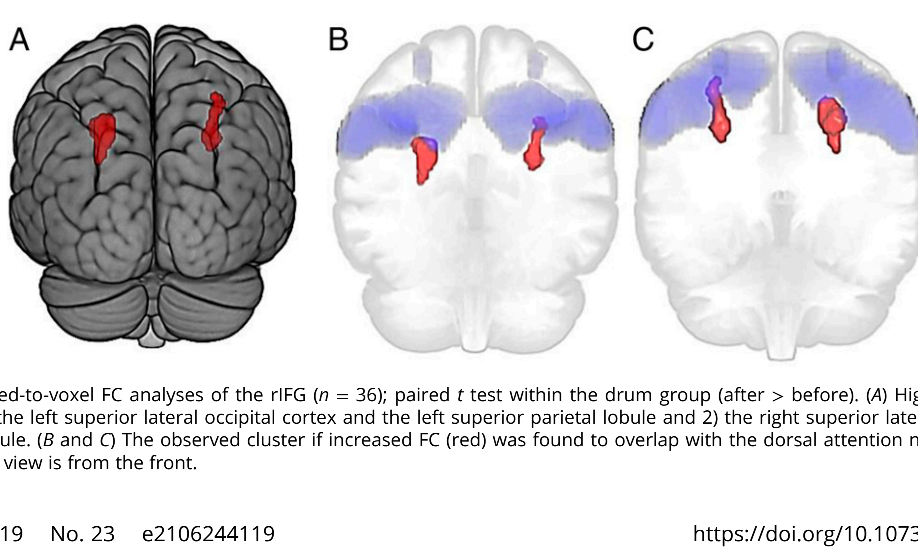

Fig. 6. Results from seed-to-voxel FC analyses of the rIFG (n = 36); paired t test within the drum group (after > before). (*A*) Higher FC was detected after drum training within 1) the left superior lateral occipital cortex and the left superior parietal lobule and 2) the right superior lateral occipital cortex and the left superior parietal lobule. (*B* and *C*) The observed cluster if increased FC (red) was found to overlap with the dorsal attention network (blue). (*B*) The view is from the back. (*C*) The view is from the front.

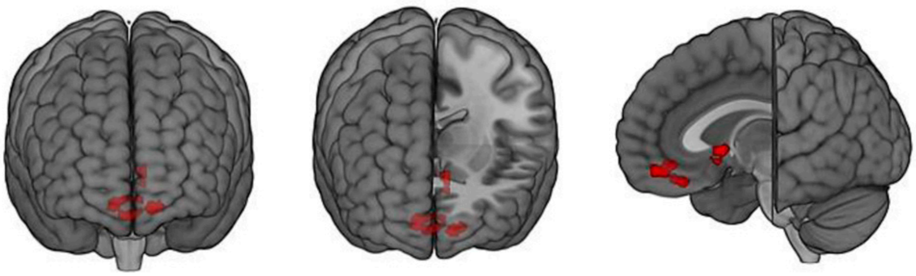

Fig. 7. Results from the MVPA analysis (n = 32) revealing FC changes after versus before intervention in the drum group compared to the control group. Clusters consisted of 1) the medial frontal cortex and the left and right paracingulate gyrus; 2) the medial frontal cortex and the subcallosal cortex; 3) the left frontal pole and the frontal medial cortex; and 4) the caudate, the left nucleus accumbens, and the subcallosal cortex.

no significant difference between the two groups at baseline with regards to autism symptoms severity. These findings suggest that the differences in timing error and hyperactivity/inattention observed between the two groups are substantial. However, future studies with a larger sample size are needed in order to corroborate the present findings.

Another limitation of this study is that the behavioral measure we used to assess participants' problem behaviors did not discriminate between hyperactivity and attentional difficulties. Instead, it offered a single measure for hyperactivity, inattention, and impulsivity-related difficulties. Future studies would benefit from selecting questionnaires that finely discriminate between the various components involved in hyperactivity and attentional difficulties so as to shape a better understanding of inhibitory control in the context of complex motor tasks. Such questionnaires could include the Conners Rating Scale (96) or the Vanderbilt ADHD Diagnostic Rating Scale (97).

Another limitation is that each participant had an individual drum tutor, which means that specific teaching and musical backgrounds might have slightly varied across tutors despite all the care taken to standardize the training. Future studies should collect further background information from each tutor in order to enhance the robustness of the design. However, it is worth noting that all tutors were required to strictly follow the exact same Rockschool syllabus and had experience of teaching individuals with neurodevelopmental disorders. Furthermore, in addition to closely meeting the specific needs of this clinical population, this ecological design highlights a robust effect of generic drum tuition on behavior and brain function through standard routes of tuition. It also eliminates potential confounds that could be observed with group tutoring such as increased sociability associated with group participation or specific methods employed by a particular tutor. We hope that this will help further inform the design of future drumming-based research using larger cohorts.

Future studies could also consider adding an active control group participating in nonmusical motor activities such as archery. This would contribute to distinguishing between motor actions and higher-order functions involved in music-based training.

Finally, even though the groups were not found to differ significantly with respect to any of the variables at baseline, it was observed that the difference in IQ between groups was close to significance for the entire dataset (n = 36; P = 0.065) with a medium effect size (Cohen's D = 0.638). Given the potential impact of IQ on learning new skills, we recommend that future studies investigating the effect of drum training on behavior and brain function consider using stratified sampling in order to guarantee more-balanced groups with respect to IQ.

Conclusion

In conclusion, this resting functional MRI study investigates the impact of a drum-based intervention on neural and behavioral outcomes in autistic adolescents. We found strong evidence that drumming not only improves the ability to delay the onset of motor responses in autistic adolescents but also reduces hyperactivity and attentional difficulties, and increases FC in brain regions responsible for inhibitory control, action-outcome monitoring, and self-regulation. The results also highlighted the central role of the prefrontal cortex in regulating motor impulsivity. We hope that these findings will inform further research studies and trials into the potential use of drum-based interventions in benefiting clinical populations with inhibition-related disorders and emotional and behavioral difficulties.

Materials and Methods

Participants. Thirty-six adolescents (age = 17.7 ± 1.3 y), with an established clinical diagnosis of ASD according to *Diagnostic and Statistical Manual,* fifth edition, criteria, participated in the study after providing written informed consent. All participants were right handed and naive to drumming, and were randomly

Table 6. Results from the MVPA analysis (n = 32)

	Cluster size	Brain areas	MNI coordinates			F	P value
			x	y	z		
MVPA						5.03	
	58	Frontal medial cortex, right paracingulate gyrus, left paracingulate gyrus	+10	+42	−14		0.025
	45	Frontal medial cortex, subcallosal cortex	−02	+32	−22		0.038
	39	Left frontal pole, frontal medial cortex	−12	+52	−14		0.043
	35	Left caudate, left accumbens, subcallosal cortex	−06	+08	+00		0.047

MNI coordinates (x, y, z) represent peaks within a cluster. Cluster size corresponds to spatial extent (i.e., number of voxels). Correction for multiple comparisons was performed using FDR correction at the cluster level.

assigned to one of two groups: drum group ($n = 19$; 12 men, 7 women; age $= 17.6 \pm 1.3$ y) and control group ($n = 17$; 12 men, 5 women; age $= 18 \pm 1.5$ y). Both groups were age and gender matched. All 36 participants took part in the drumming assessment, psychological testing, and MRI scans. However, the drumming performance analysis was carried out on a subset of 32 participants, due to one participant not being able to attend the "post" drumming assessment session and three participants misunderstanding the instructions during the drumming assessments. This subset of participants comprised 17 participants for the drum group (11 men, 6 women, age $= 17.59 \pm 1.3$ y) and 15 participants for the control group (11 men, 4 women, age $= 17.9 \pm 1.6$ y).

Ethical approval was granted by the King's College London Research Ethics Committee.

Procedure. All participants attended two scanning sessions at the Centre for Neuroimaging Sciences (Institute of Psychiatry, Psychology and Neuroscience; King's College London). In each scanning session, participants received a 20-min drumming assessment, a 45-min MRI scan, and a battery of neuropsychological tests. Furthermore, a parent was asked to fill in two questionnaires about the participant's sociocommunication abilities and repetitive and restricted behaviors. After this initial assessment, the drum group received drum training (a 45-min lesson, twice a week over an 8-wk period), while the control group did not. After the drum training had finished, all participants were invited to come back to the Centre for Neuroimaging Sciences to undergo the same testing battery (drumming assessment, neuropsychological testing, questionnaires, and MRI scan) as on their first visit.

Before attending their first scanning session at the Centre for Neuroimaging Sciences, participants' degree of handedness was assessed using the Edinburgh Handedness Inventory Short Form (98). Additionally, in order to control for musical experience, a self-report questionnaire was created. Participants were asked to provide details about their previous experience of playing a musical instrument, dancing, and singing, if any. The Autism Quotient (99), the State-Trait Anxiety Inventory – Trait subscale (100), and the Sensory Perception Quotient (101) were also employed in order to quantify autism symptoms severity, trait anxiety levels, and atypical sensory sensitivity frequently observed in ASD (27, 28). Finally, an IQ measure, the Wechsler Abbreviated Scale of Intelligence - Second Edition (102), was administered to all participants by a chartered psychologist in order to formally verify that none of the participants had a learning disability, in line with our inclusion criteria.

Assessment and Analysis.

Drumming assessment and practice. Drumming ability was assessed at the Centre for Neuroimaging Sciences before and after drumming tuition. All before and after drum tests were performed on the same volume-controlled, electronic drum kit (TD9, Roland) with a standard right-handed five-piece configuration comprising a snare drum, three tom-toms, hi-hat, ride cymbal, crash cymbal, and bass drum. The drum tests were recorded using a Musical Instrument Digital Interface (MIDI) sequencer (Cubase Pro-9.5) and converted to exportable MIDI files, each containing a single exercise. Matlab MIDI Toolbox 1.1 (103) was used to import the files into the Matlab environment, and custom code was used for extracting data from the performance. The drumming assessment consisted of nine exercises which involved playing on the snare drum with the right hand, the left hand, and alternate hands to the metronome set at three tempi: 60, 90, and 120 beats per minute (bpm). The order for these exercises was counterbalanced (Latin square). The analysis of the drumming performance was carried out on a subset of 32 participants.

Drumming improvement was assessed quantitatively as the reduction of the onset error between the after and the before sessions. More specifically, the onset error was calculated as the absolute difference, in milliseconds, between the actual note played by the drummer and the expected note (click), across the three tempi and the nine exercises. In this paper, this measure will be referred to as timing error. The difference in timing error between the before and the after sessions provides a robust behavioral measure to quantify the improvement of the participant in learning how to play the expected model, assuming that the simplicity of the drum exercises posed a negligible delay between the intention to play and the completion of the movement. Furthermore, we also evaluated whether the timing error was the result of anticipation or delay. We hypothesized that a generalized tendency to anticipate the drum hit could reflect difficulties in delaying the onset of motor responses. Unlike timing error, this relative timing error measure uses the nonabsolute difference between the actual note and the expected note, and comprises a range of positive and negative values: A positive value indicates delay, while a negative value indicates anticipation. The midway of the interstimulus interval was used as the threshold for the error range. Thus, scores obtained for each drumming measure ranged between 0 and 500 ms for 60 bpm, 0 and 375 ms for 90 bpm, and 0 and 250 ms for 120 bpm for the timing error, and between −500 and 500 ms for 60 bpm, −375 and 375 ms for 90 bpm, and −250 ms and 250 ms for 120 bpm for the relative timing error measure. Extra taps observed in the exercises resulted from the rebound of the stick on the drum and were removed on the basis that they were a continuation of a single musical gesture. Missing notes were disregarded because the protocol did not specify to avoid interruptions or a precise starting bar and end bar. Scores were averaged across all exercises and all tempi.

Following the first drumming assessment, the drum group took part in two 45-min drumming lessons per week over 8 wk. Each lesson was delivered on a one-to-one basis either at the participant's home or at the professional drum tutor's drumming studio. Participants were recruited from various areas across the United Kingdom. In order to limit travel time and inconvenience, each participant was assigned to a drum tutor based less than 30 min away from their home. A total of 18 drum tutors were recruited, and one tutor taught two participants. The lessons comprised individualized learning following the standardized Rockschool drumming syllabus. All tutors were carefully selected based on their previous experience of teaching individuals with neurodevelopmental disorders and carrying out tuition following the Rockschool syllabus for beginners. The complexity of drumming tuition was increased on a weekly basis in line with participants' demonstration of improved drumming coordination and technique. The control participants were asked not to take part in any musical activities. After the 8 wk, all of the participants came back for a second drumming assessment, neuropsychological testing, questionnaires, and an MRI scan.

Statistical analyses of the drumming data extracted in Matlab were performed using SPSS (SPSS version 18). Independent sample t tests and paired t tests were used to determine baseline differences and the effects of drum training within groups. To test whether there was a significant interaction of group over time (time*group), we also carried out a repeated-measures ANOVA by specifying "time" as a within-subjects contrast (i.e., before vs. after drum training) and "group" as a between-subjects contrast (drum group vs. control group). Significance was set at $P < 0.05$. Finally, in order to further evaluate observed effects, we also calculated effect sizes (Cohen's D for paired t tests and partial eta squared η^2 for ANOVAs) using SPSS (SPSS version 18).

Psychological measures. Two separate measures were used to investigate participants' social communication abilities and levels of restricted, repetitive behaviors. These psychological questionnaires were completed by parents on both visits.

Social Skills Improvement System—Rating Scales (104). The parent version of the Social Skills Improvement System (SSIS) is a 15-min paper and pencil, multidimensional assessment that measures overall social skills, including seven subscales (communication, cooperation, assertion, responsibility, empathy, engagement, and self-control), and overall problem behaviors, including five subscales (externalizing, bullying, hyperactivity/inattention, internalizing, and autism spectrum). Each question assessed the frequency of the behavior on a four-point Likert scale (never, seldom, often, almost always).

A score was obtained for each of the subscales as well as for overall social skills, by summing up scores obtained in each of the seven subscales, and overall problem behaviors, by summing up scores obtained in each of the five subscales.

Repetitive Behavior Scale-Revised (105). The Repetitive Behavior Scale-Revised (RBS) is a caregiver-report questionnaire that assesses restricted and repetitive behaviors of autistic individuals. It consists of 43 items that measure six subscales: stereotyped behavior, self-injurious behavior, compulsive behavior, ritualistic behavior, sameness behavior, and restricted behavior. Each item is rated on a four-point scale (behavior does not occur, behavior occurs and is a mild problem, behavior occurs and is a moderate problem, and behavior occurs and is a severe problem).

A score was obtained for each subscale in addition to a total RBS score which was computed by summing up scores obtained on each of the subscales.

On both visits, we also collected some information on participants' levels of state anxiety, ataxia, and difficulties that could be attributed to cerebellar dysfunction. More specifically, participants filled in the State-Trait Anxiety Inventory – State subscale (100), and a chartered psychologist administered the Brief Ataxia Rating Scale (106) and the Cerebellar Cognitive Affective Syndrome scale (107). However, in this paper, we will specifically focus on the SSIS and the RBS described above.

Statistical analyses of the psychological data were performed on all 36 participants, using SPSS (SPSS version 18). Data were assessed for normality using the Shapiro–Wilk test and, as they were acceptably normal, a repeated-measures ANOVA was used for investigating the interaction of group over time (time*-group); and independent sample *t* tests were used to ensure there were no baseline differences between the two groups. Significance was set at $P < 0.05$.

MRI data acquisition. All participants were scanned in a 3T MR scanner (Discovery MR750, General Electric). All participants underwent an anatomical T1-weighted MRI using a gradient-echo sequence with the following scan parameters: 196 sagittal slices, time repetition = 7.3 ms, time echo = 3 ms, time to inversion = 400 ms, flip angle = 11°, field of view = 270 mm^2, matrix size = 256 × 256, voxel size = 1 × 1 × 1 mm^3, and slice thickness = 1.2 mm. The rs-fMRI data were collected using an echo-planar imaging sequence with the following scan parameters: 180 volumes, descending slice order, time repetition = 2 s, time echo = 30 ms, flip angle = 75°, field of view = 211 mm^2, matrix size = 64 × 64, voxel size = 3 × 3 × 3 mm^3, and slice thickness = 3 mm.

During acquisition of the rs sequence, the participants were asked to look at a cross on the screen in a wakeful resting state and were provided with headphones and earplugs in order to reduce the acoustic noise generated by the scanner.

MRI data preprocessing. Statistical Parametric Mapping (SPM12) and the CONN functional connectivity toolbox Version 18b (https://www.nitrc.org/projects/conn) (108) were used to preprocess and analyze the anatomical and functional data. Preprocessing of the functional data included a slice-timing correction, realignment (motion correction), registration to structural images, spatial normalization into the Montreal Neurological Institute (MNI) standardized space, and smoothing with a Gaussian filter of 5.0 mm spatial full width at half maximum value. A conventional band-pass filter over a low-frequency window of interest (0.008 to 0.09) was also applied to the rs time series. A CompCor strategy (109) was then carried out, extracting signal to noise from the white matter and cerebrospinal fluid by principal component analysis (PCA) without affecting intrinsic FC (110). The white matter, the cerebrospinal fluid, and the motion parameters were included in the model and considered as covariates of no interest.

Seed-to-voxel analyses. Seed-to-voxel analyses typically consist of computing the FC between one seed and all other voxels of the brain. For this analysis, two seeds were identified based on findings from the analyses of the drumming assessments and psychological measures. The rDLPFC was chosen because it is a key hub of the central executive network, a network which activates during typical fMRI tasks involving EFs. It is involved in attentional control, impulsivity, attention shifting, and response inhibition (55–57), and it has a specific role in multisensory attention (55). The seed region was represented as a 6-mm sphere (MNI coordinates: x = 50, y = 18, z = 44). More specifically, the MNI coordinates of this seed were chosen based on previous research showing its key implication in multisensory auditory–visual attention tasks such as "oddball" tasks (55). The second region of interest (ROI) which was used as a seed was the rIFG (MNI coordinates: x = 54, y = 28, z = 1). It was chosen due to its key involvement in inhibitory control, sustained attention, hyperactivity, behavioral impulsivity, and timing (111–117). In particular, it is involved in inhibitory control tasks in musicians compared to nonmusicians (118), and this specific seed plays a major role in the withholding of responses in the context of go/no-go tasks (119). The ROI was anatomically defined, based on the Harvard–Oxford cortical atlas implemented in the CONN toolbox (108).

For each seed, correlations maps of the whole brain were created for each of the 36 subjects, by extracting the mean signal time course from the seed and computing Pearson's correlations coefficients with the time course of all other voxels of the brain. The correlation maps were z transformed using the Fisher transformation to allow for second-level analyses.

As Klöppel et al. (120) and Koelsch et al. (121) have shown that age, gender, and handedness could affect musical training, age, gender, and degree of handedness were included as covariates in all MRI analyses.

A time*group interaction (2 × 2 ANCOVA) was performed in order to look at the effects between the two groups over time. Following this, a paired *t* test was carried out using the CONN toolbox, in order to directly compare effects over time (i.e., before drum training vs. after drum training scores) within the drum group.

In order to explore whether clusters of increased FC overlapped with the dorsal attention network, the dorsal attention network mask was extracted from the CONN toolbox.

MRIcroGL (https://www.nitrc.org/projects/mricrogl/) was used to create the statistical overlay images for both seed-to-voxel and voxel-to-voxel analyses.

Voxel-to-voxel analysis. Finally, the last step of the analysis consisted in investigating how drumming performance related to changes in FC between the two groups over time (time*group interaction). For that purpose, a data-driven MVPA (multivariate pattern analysis) approach (108) was performed, using timing error as a regressor. For this MRI analysis specifically, it is important to note that the drumming performance data were used, and, therefore, this analysis was performed on the same subset of 32 participants.

By adopting an MVPA approach, the experimental disadvantage of a user selection bias in targeting specific brain regions was eliminated. In this approach, for each voxel, a low-dimensional multivariate representation characterizing the connectivity pattern between this voxel and the rest of the brain was derived. This representation was defined by computing the pairwise connectivity pattern between each voxel and the rest of the brain and using PCA to characterize those patterns. Finally, an F test was performed on all MVPA components in a single second-level analysis to identify the voxels that show significant differences in connectivity patterns between the two groups over time (time*group interaction) while taking into account the specific degree of change in drumming performance. In other words, this method specifically highlighted how differences in drumming performance between groups over time are reflected at the brain level. More technical details and an example of this method can be found in refs. 122 and 123.

All MRI results were thresholded at a voxel-wise $P < 0.001$ and, at the cluster extent $P < 0.05$, FDR corrected.

Data Availability. Anonymized rs-fMRI data are available at https://osf.io/92dxb/.

ACKNOWLEDGMENTS. We thank The Waterloo Foundation for their financial support and guidance during the course of this project. We acknowledge Clem Burke and Mark Richardson from the Clem Burke Drumming Project for their continued support and enthusiasm for our drum-related research. We thank all of the participants as well as their carers and drum tutors, for their dedication to this research. We thank the Wellcome Trust and the National Institute for Health Research (NIHR) Maudsley Biomedical Research Centre at South London and Maudsley NHS Foundation Trust and King's College London for their continued support of our neuroimaging research endeavors. The views expressed are those of the author(s) and not necessarily those of the NHS, the NIHR, or the Department of Health and Social Care.

1. American Psychiatric Association, *Diagnostic and Statistical Manual of Mental Disorders* (American Psychiatric Publishing, Arlington, VA, ed. 5, 2013).
2. C. E. Rice *et al.*, Evaluating changes in the prevalence of the autism spectrum disorders (ASDs). *Public Health Rev.* **34**, 1–22 (2012).
3. J. Baio *et al.*, Prevalence of autism spectrum disorder among children aged 8 years – Autism and developmental disabilities monitoring network, 11 sites, United States, 2014. *MMWR Surveill. Summ.* **67**, 1–12 (2018). Correction in: *MMWR Surveill. Summ.* **69**, 503 (2020).
4. B. Alallawi, R. P. Hastings, G. Gray, A systematic scoping review of social, educational and psychological research on individuals with autism spectrum disorder and their family members in Arab countries and cultures. *Rev. J. Autism Dev. Disord.* **7**, 364–382 (2018).
5. A. V. Buescher, Z. Cidav, M. Knapp, D. S. Mandell, Costs of autism spectrum disorders in the United Kingdom and the United States. *JAMA Pediatr.* **168**, 721–728 (2014).
6. J. L. Taylor, N. A. Henninger, Frequency and correlates of service access among youth with autism transitioning to adulthood. *J. Autism Dev. Disord.* **45**, 179–191 (2015).
7. L. Kenny *et al.*, Which terms should be used to describe autism? Perspectives from the UK autism community. *Autism* **20**, 442–462 (2016).
8. S. P. Singh, Transition of care from child to adult mental health services: The great divide. *Curr. Opin. Psychiatry* **22**, 386–390 (2009).
9. J. L. Taylor, M. M. Seltzer, Developing a vocational index for adults with autism spectrum disorders. *J. Autism Dev. Disord.* **42**, 2669–2679 (2012).
10. P. T. Shattuck, M. Wagner, S. Narendorf, P. Sterzing, M. Hensley, Post-high school service use among young adults with an autism spectrum disorder. *Arch. Pediatr. Adolesc. Med.* **165**, 141–146 (2011).
11. M. M. Seltzer, P. Shattuck, L. Abbeduto, J. S. Greenberg, Trajectory of development in adolescents and adults with autism. *Ment. Retard. Dev. Disabil. Res. Rev.* **10**, 234–247 (2004).

12. N. C. Adams, C. Jarrold, Inhibition in autism: Children with autism have difficulty inhibiting irrelevant distractors but not prepotent responses. *J. Autism Dev. Disord.* **42**, 1052–1063 (2012).
13. Y. Agam, R. M. Joseph, J. J. Barton, D. S. Manoach, Reduced cognitive control of response inhibition by the anterior cingulate cortex in autism spectrum disorders. *Neuroimage* **52**, 336–347 (2010).
14. M. C. Anderson, B. Levy, Suppressing unwanted memories. *Curr. Dir. Psychol. Sci.* **18**, 189–194 (2009).
15. A. Diamond, Executive functions. *Annu. Rev. Psychol.* **64**, 135–168 (2013).
16. N. Eisenberg, Emotion, regulation, and moral development. *Annu. Rev. Psychol.* **51**, 665–697 (2000).
17. A. Shields, D. Cicchetti, Reactive aggression among maltreated children: The contributions of attention and emotion dysregulation. *J. Clin. Child Psychol.* **27**, 381–395 (1998).
18. E. L. Hill, Executive dysfunction in autism. *Trends Cogn. Sci.* **8**, 26–32 (2004).
19. L. M. Schmitt *et al.*, Familiality of behavioral flexibility and response inhibition deficits in autism spectrum disorder (ASD). *Mol. Autism* **10**, 47 (2019).
20. A. S. Vara, E. W. Pang, J. Vidal, E. Anagnostou, M. J. Taylor, Neural mechanisms of inhibitory control continue to mature in adolescence. *Dev. Cogn. Neurosci.* **10**, 129–139 (2014).
21. F. Velasquez *et al.*, Neural correlates of emotional inhibitory control in autism spectrum disorders. *Res. Dev. Disabil.* **64**, 64–67 (2017).
22. E. A. Demetriou *et al.*, Autism spectrum disorders: A meta-analysis of executive function. *Mol. Psychiatry* **23**, 1198–1204 (2018).
23. M. Solomon *et al.*, The development of the neural substrates of cognitive control in adolescents with autism spectrum disorders. *Biol. Psychiatry* **76**, 412–421 (2014).
24. M. W. Mosconi *et al.*, Impaired inhibitory control is associated with higher-order repetitive behaviors in autism spectrum disorders. *Psychol. Med.* **39**, 1559–1566 (2009).
25. M. A. Mostert-Kerckhoffs, W. G. Staal, R. H. Houben, M. V. de Jonge, Stop and change: Inhibition and flexibility skills are related to repetitive behavior in children and young adults with autism spectrum disorders. *J. Autism Dev. Disord.* **45**, 3148–3158 (2015).
26. W. Voorhies *et al.*, Aberrant functional connectivity of inhibitory control networks in children with autism spectrum disorder. *Autism Res.* **11**, 1468–1478 (2018).
27. R. L. Moseley, R. Hitchiner, J. A. Kirkby, Self-reported sex differences in high-functioning adults with autism: A meta-analysis. *Mol. Autism* **9**, 33 (2018).
28. S. L. J. Jackson, L. Hart, J. T. Brown, F. R. Volkmar, Brief report: Self-reported academic, social, and mental health experiences of post-secondary students with autism spectrum disorder. *J. Autism Dev. Disord.* **48**, 643–650 (2018).
29. L. H. Quek, K. Sofronoff, J. Sheffield, A. White, A. Kelly, Co-occurring anger in young people with Asperger's syndrome. *J. Clin. Psychol.* **68**, 1142–1148 (2012).
30. V. Van Hees, T. Moyson, H. Roeyers, Higher education experiences of students with autism spectrum disorder: Challenges, benefits and support needs. *J. Autism Dev. Disord.* **45**, 1673–1688 (2015).
31. J. Slater, A. Azem, T. Nicol, B. Swedenborg, N. Kraus, Variations on the theme of musical expertise: Cognitive and sensory processing in percussionists, vocalists and non-musicians. *Eur. J. Neurosci.* **45**, 952–963 (2017).
32. A. Ronald, H. Larsson, H. Anckarsäter, P. Lichtenstein, Symptoms of autism and ADHD: A Swedish twin study examining their overlap. *J. Abnorm. Psychol.* **123**, 440–451 (2014).
33. T. J. Polderman *et al.*, Attentional switching forms a genetic link between attention problems and autistic traits in adults. *Psychol. Med.* **43**, 1985–1996 (2013).
34. E. Bialystok, A. M. Depape, Musical expertise, bilingualism, and executive functioning. *J. Exp. Psychol. Hum. Percept. Perform.* **35**, 565–574 (2009).
35. J. A. Bugos, W. M. Perlstein, C. S. McCrae, T. S. Brophy, P. H. Bedenbaugh, Individualized piano instruction enhances executive functioning and working memory in older adults. *Aging Ment. Health* **11**, 464–471 (2007).
36. K. E. Williams, Moving to the beat: Using music, rhythm and movement to enhance self-regulation in early childhood classrooms. *Int. J. Early Child.* **50**, 85–100 (2018).
37. T. Lesiuk, Music perception ability of children with executive function deficits. *Psychol. Music* **43**, 530–544 (2015).
38. I. D. Colley, P. E. Keller, A. R. Halpern, Working memory and auditory imagery predict sensorimotor synchronization with expressively timed music. *Q. J. Exp. Psychol.* **71**, 1781–1796 (2017).
39. J. Sandford, A. Turner, *IVA+ Plus: Interpretation Manual* (BrainTrain, Chesterfield, VA, 1994).
40. R. G. Lowry, B. J Hale, S. B. Draper, M. S. Smith, Rock drumming enhances motor and psychosocial skills of children with emotional and behavioral difficulties. *Int. J. Dev. Disabil.* **65**, 152–161 (2018).
41. S. Draper *et al.*, "The effects of a rock drumming intervention on children with additional educational needs" in *European College of Sport Science Conference 2020*, F. Dela, E. Muller, E. Tsolakidis, Eds., 236 (2020). OP-SH01 S4.
42. L. Chukoskie, J. Townsend, M. Westerfield, Motor skill in autism spectrum disorders: A subcortical view. *Int. Rev. Neurobiol.* **113**, 207–249 (2013).
43. R. Downey, M. J. Rapport, Motor activity in children with autism: A review of current literature. *Pediatr. Phys. Ther.* **24**, 2–20 (2012).
44. A. Lane, K. Harpster, J. Heathcock, Motor characteristics of young children referred for possible autism spectrum disorder. *Pediatr. Phys. Ther.* **24**, 21–29 (2012).
45. M. Lloyd, M. MacDonald, C. Lord, Motor skills of toddlers with autism spectrum disorders. *Autism* **17**, 133–146 (2013).
46. A. M. Dowd, J. L. McGinley, J. R. Taffe, N. J. Rinehart, Do planning and visual integration difficulties underpin motor dysfunction in autism? A kinematic study of young children with autism. *J. Autism Dev. Disord.* **42**, 1539–1548 (2012).
47. E. M. Sokhadze, A. Tasman, G. E. Sokhadze, A. S. El-Baz, M. F. Casanova, Behavioral, cognitive, and motor preparation deficits in a visual cued spatial attention task in autism spectrum disorder. *Appl. Psychophysiol. Biofeedback* **41**, 81–92 (2016).
48. L. Gallo-Lopez, L. C. C. Rubin, *Play-Based Interventions for Children and Adolescents on the Autism Spectrum* (Taylor & Francis, New York, NY, 2012).
49. J. M. Holloway, T. M. Long, F. Biasini, Relationships between gross motor skills and social function in young boys with autism spectrum disorder. *Pediatr. Phys. Ther.* **30**, 184–190 (2018).
50. S. E. De La Rue, S. B. Draper, C. R. Potter, M. S. Smith, Energy expenditure in rock/pop drumming. *Int. J. Sports Med.* **34**, 868–872 (2013).
51. B. B. Bittman *et al.*, Composite effects of group drumming music therapy on modulation of neuroendocrine-immune parameters in normal subjects. *J. Altern. Ther.* **7**, 38–47 (2001).
52. N. N. Stone, Hand-drumming to build community: The story of the Whittier Drum Project. *New Dir. Youth Dev.* **106**, 73–83 (2005).
53. A. Amad *et al.*, Motor learning induces plasticity in the resting brain—Drumming up a connection. *Cereb. Cortex* **27**, 2010–2021 (2017).
54. S. Ascenso, R. Perkins, L. Atkins, D. Fancourt, A. Williamon, Promoting well-being through group drumming with mental health service users and their carers. *Int. J. Qual. Stud. Health Well-Being* **13**, 1484219 (2018).
55. T. Chen *et al.*, Role of the anterior insular cortex in integrative causal signaling during multisensory auditory-visual attention. *Eur. J. Neurosci.* **41**, 264–274 (2015).
56. K. Rubia, Cognitive neuroscience of attention deficit hyperactivity disorder (ADHD) and its clinical translation. *Front. Hum. Neurosci.* **12**, 100 (2018).
57. E. G. Duerden *et al.*, Neural correlates of inhibition of socially relevant stimuli in adults with autism spectrum disorder. *Brain Res.* **1533**, 80–90 (2013).
58. T. Piccoli *et al.*, The Default Mode Network and the Working Memory Network are not anti-correlated during all phases of a working memory task. *PLoS One* **10**, e0123354 (2015).
59. W. Cheng *et al.*, Functional connectivity of the precuneus in unmedicated patients with depression. *Biol. Psychiatry Cogn. Neurosci. Neuroimaging* **3**, 1040–1049 (2018).
60. E. A. Olson, R. H. Kaiser, D. A. Pizzagalli, S. L. Rauch, I. M. Rosso, Regional prefrontal resting-state functional connectivity in posttraumatic stress disorder. *Biol. Psychiatry Cogn. Neurosci. Neuroimaging* **4**, 390–398 (2019).
61. A. P. King *et al.*, Altered default mode network (DMN) resting state functional connectivity following a mindfulness-based exposure therapy for posttraumatic stress disorder (PTSD) in combat veterans of Afghanistan and Iraq. *Depress. Anxiety* **33**, 289–299 (2016).
62. R. E. Beaty, M. Benedek, S. B. Kaufman, P. J. Silvia, Default and executive network coupling support creative idea production. *Sci. Rep.* **5**, 10964 (2015).
63. S. Tanaka, E. Kirino, Functional connectivity of the precuneus in female university students with long-term musical training. *Front. Hum. Neurosci.* **10**, 328 (2016).
64. E. L. Hill, U. Frith, Understanding autism: Insights from mind and brain. *Philos. Trans. R. Soc. Lond. B Biol. Sci.* **358**, 281–289 (2003).
65. M. Assaf *et al.*, Abnormal functional connectivity of default mode sub-networks in autism spectrum disorder patients. *Neuroimage* **53**, 247–256 (2010).
66. D. C. Rojas *et al.*, Regional gray matter volumetric changes in autism associated with social and repetitive behavior symptoms. *BMC Psychiatry* **6**, 56 (2006).
67. G. Erdogan, Q. Chen, F. E. Garcea, B. Z. Mahon, R. A. Jacobs, Multisensory part-based representations of objects in human lateral occipital cortex. *J. Cogn. Neurosci.* **28**, 869–881 (2016).
68. K. Nagy, M. W. Greenlee, G. Kovács, The lateral occipital cortex in the face perception network: An effective connectivity study. *Front. Psychol.* **3**, 141 (2012).
69. L. E. Libero *et al.*, The role of mirroring and mentalizing networks in mediating action intentions in autism. *Mol. Autism* **5**, 50 (2014).
70. M. V. Lombardo *et al.*, Different functional neural substrates for good and poor language outcome in autism. *Neuron* **86**, 567–577 (2015).
71. M. Jung *et al.*, Decreased structural connectivity and resting-state brain activity in the lateral occipital cortex is associated with social communication deficits in boys with autism spectrum disorder. *Neuroimage* **190**, 205–212 (2019).
72. M. B. Nebel *et al.*, Intrinsic visual-motor synchrony correlates with social deficits in autism. *Biol. Psychiatry* **79**, 633–641 (2016).
73. R. K. Kana, T. A. Keller, N. J. Minshew, M. A. Just, Inhibitory control in high-functioning autism: Decreased activation and underconnectivity in inhibition networks. *Biol. Psychiatry* **62**, 198–206 (2007).
74. R. A. Müller, N. Kleinhans, N. Kemmotsu, K. Pierce, E. Courchesne, Abnormal variability and distribution of functional maps in autism: An FMRI study of visuomotor learning. *Am. J. Psychiatry* **160**, 1847–1862 (2003).
75. B. G. Travers, R. K. Kana, L. G. Klinger, C. L. Klein, M. R. Klinger, Motor learning in individuals with autism spectrum disorder: Activation in superior parietal lobule related to learning and repetitive behaviors. *Autism Res.* **8**, 38–51 (2015).
76. R. Gatti *et al.*, The effect of action observation/execution on mirror neuron system recruitment: An fMRI study in healthy individuals. *Brain Imaging Behav.* **11**, 565–576 (2017).
77. J. Grezes, Top down effect of strategy on the perception of human biological motion: A PET investigation. *Cogn. Neuropsychol.* **15**, 553–582 (1998).
78. A. Jack, J. P. Morris, Neocerebellar contributions to social perception in adolescents with autism spectrum disorder. *Dev. Cogn. Neurosci.* **10**, 77–92 (2014).
79. S. H. Johnson-Frey *et al.*, Actions or hand-object interactions? Human inferior frontal cortex and action observation. *Neuron* **39**, 1053–1058 (2003).
80. M. R. G. Brown *et al.*, fMRI investigation of response inhibition, emotion, impulsivity, and clinical high-risk behavior in adolescents. *Front. Syst. Neurosci.* **9**, 124 (2015).
81. N. S. Hinvest, R. Elliott, S. McKie, I. M. Anderson, Neural correlates of choice behavior related to impulsivity and venturesomeness. *Neuropsychologia* **49**, 2311–2320 (2011).
82. E. F. Coccaro, M. S. McCloskey, D. A. Fitzgerald, K. L. Phan, Amygdala and orbitofrontal reactivity to social threat in individuals with impulsive aggression. *Biol. Psychiatry* **62**, 168–178 (2007).
83. K. N. Ochsner, J. J. Gross, Cognitive emotion regulation: Insights from social cognitive and affective neuroscience. *Curr. Dir. Psychol. Sci.* **17**, 153–158 (2008).
84. C. Korponay *et al.*, Neurobiological correlates of impulsivity in healthy adults: Lower prefrontal gray matter volume and spontaneous eye-blink rate but greater resting-state functional connectivity in basal ganglia-thalamo-cortical circuitry. *Neuroimage* **157**, 288–296 (2017).
85. Y. T. Cho *et al.*, Nucleus accumbens, thalamus and insula connectivity during incentive anticipation in typical adults and adolescents. *Neuroimage* **66**, 508–521 (2013).
86. Y. Qiu *et al.*, Reduced regional homogeneity in bilateral frontostriatal system relates to higher impulsivity behavior in codeine-containing cough syrups dependent individuals. *PLoS One* **8**, e78738 (2013).
87. A. Ciaramidaro *et al.*, Transdiagnostic deviant facial recognition for implicit negative emotion in autism and schizophrenia. *Eur. Neuropsychopharmacol.* **28**, 264–275 (2018).
88. M. C. Lai *et al.*; MRC AIMS Consortium, Neural self-representation in autistic women and association with 'compensatory camouflaging.' *Autism* **23**, 1210–1223 (2019).
89. M. V. Lombardo *et al.*; MRC AIMS Consortium, Atypical neural self-representation in autism. *Brain* **133**, 611–624 (2010).
90. K. O. Yeates *et al.*, Short- and long-term social outcomes following pediatric traumatic brain injury. *J. Int. Neuropsychol. Soc.* **10**, 412–426 (2004).

91. A. Levan, L. Baxter, C. B. Kirwan, G. Black, S. D. Gale, Right frontal pole cortical thickness and social competence in children with chronic traumatic brain injury: Cognitive proficiency as a mediator. *J. Head Trauma Rehabil.* **30**, E24–E31 (2015).
92. F. Dambacher *et al.*, The role of right prefrontal and medial cortex in response inhibition: Interfering with action restraint and action cancellation using transcranial magnetic brain stimulation. *J. Cogn. Neurosci.* **26**, 1775–1784 (2014).
93. L. Rademacher, A. Salama, G. Gründer, K. N. Spreckelmeyer, Differential patterns of nucleus accumbens activation during anticipation of monetary and social reward in young and older adults. *Soc. Cogn. Affect. Neurosci.* **9**, 825–831 (2014).
94. I. Kokal, A. Engel, S. Kirschner, C. Keysers, Synchronized drumming enhances activity in the caudate and facilitates prosocial commitment – If the rhythm comes easily. *PLoS One* **6**, e27272 (2011).
95. G. S. Dichter, J. A. Richey, A. M. Rittenberg, A. Sabatino, J. W. Bodfish, Reward circuitry function in autism during face anticipation and outcomes. *J. Autism Dev. Disord.* **42**, 147–160 (2012).
96. C. K. Conners, *Conners' Rating Scales-Revised Technical Manual* (Multi-Health Systems, North Tonawanda, NY, 1997).
97. M. L. Wolraich, D. E. Bard, B. Neas, M. Doffing, L. Beck, The psychometric properties of the Vanderbilt attention-deficit hyperactivity disorder diagnostic teacher rating scale in a community population. *J. Dev. Behav. Pediatr.* **34**, 83–93 (2013).
98. J. F. Veale, Edinburgh Handedness Inventory – Short Form: A revised version based on confirmatory factor analysis. *Laterality* **19**, 164–177 (2014).
99. S. Baron-Cohen, S. Wheelwright, R. Skinner, J. Martin, E. Clubley, The autism-spectrum quotient (AQ): Evidence from Asperger syndrome/high-functioning autism, males and females, scientists and mathematicians. *J. Autism Dev. Disord.* **31**, 5–17 (2001).
100. C. D. Spielberger, R. L. Gorsuch, R. E. Lushene, *Manual for the State-Trait Anxiety Inventory* (Consulting Psychologists Press, Palo Alto, CA, 1970).
101. T. Tavassoli, R. A. Hoekstra, S. Baron-Cohen, The Sensory Perception Quotient (SPQ): Development and validation of a new sensory questionnaire for adults with and without autism. *Mol. Autism* **5**, 29 (2014).
102. D. Wechsler, *Wechsler Abbreviated Scale of Intelligence – Second Edition* (NCS Pearson, 2011).
103. T. Eerola, P. Toiviainen, MIDI Toolbox: MATLAB Tools for Music (2004). https://users.cs.cf.ac.uk/Dave.Marshall/Multimedia/exercises_BSC/MIDI_Toolbox_Manual.pdf. Accessed 16 May 2022.
104. S. N. Elliott, F. M. Gresham, "Social skills improvement system" in *Encyclopedia of Autism Spectrum Disorders*, F. R. Volkmar, Ed. (Springer, 2013), pp. 116–139.
105. J. W. Bodfish, F. J. Symons, D. E. Parker, M. H. Lewis, Varieties of repetitive behavior in autism: Comparisons to mental retardation. *J. Autism Dev. Disord.* **30**, 237–243 (2000).
106. J. D. Schmahmann, R. Gardner, J. MacMore, M. G. Vangel, Development of a brief ataxia rating scale (BARS) based on a modified form of the ICARS. *Mov. Disord.* **24**, 1820–1828 (2009).
107. F. Hoche, X. Guell, M. G. Vangel, J. C. Sherman, J. D. Schmahmann, The cerebellar cognitive affective/Schmahmann syndrome scale. *Brain* **141**, 248–270 (2018).
108. S. Whitfield-Gabrieli, A. Nieto-Castanon, *Conn*: A functional connectivity toolbox for correlated and anticorrelated brain networks. *Brain Connect.* **2**, 125–141 (2012).
109. Y. Behzadi, K. Restom, J. Liau, T. T. Liu, A component based noise correction method (CompCor) for BOLD and perfusion based fMRI. *Neuroimage* **37**, 90–101 (2007).
110. X. J. Chai, A. N. Castañón, D. Ongür, S. Whitfield-Gabrieli, Anticorrelations in resting state networks without global signal regression. *Neuroimage* **59**, 1420–1428 (2012).
111. A. A. Alegria *et al.*, Real-time fMRI neurofeedback in adolescents with attention deficit hyperactivity disorder. *Hum. Brain Mapp.* **38**, 3190–3209 (2017).
112. K. Hugdahl, M. E. Raichle, A. Mitra, K. Specht, On the existence of a generalized non-specific task-dependent network. *Front. Hum. Neurosci.* **9**, 430 (2015).
113. H. Kim, Involvement of the dorsal and ventral attention networks in oddball stimulus processing: A meta-analysis. *Hum. Brain Mapp.* **35**, 2265–2284 (2014).
114. J. Radua, N. O. Del Pozo, J. Gómez, F. Guillen-Grima, F. Ortuño, Meta-analysis of functional neuroimaging studies indicates that an increase of cognitive difficulty during executive tasks engages brain regions associated with time perception. *Neuropsychologia* **58**, 14–22 (2014).
115. K. Rubia *et al.*, Functional connectivity changes associated with fMRI neurofeedback of right inferior frontal cortex in adolescents with ADHD. *Neuroimage* **188**, 43–58 (2019).
116. K. Rubia *et al.*, Hypofrontality in attention deficit hyperactivity disorder during higher-order motor control: A study with functional MRI. *Am. J. Psychiatry* **156**, 891–896 (1999).
117. K. Rubia, A. B. Smith, M. J. Brammer, B. Toone, E. Taylor, Abnormal brain activation during inhibition and error detection in medication-naive adolescents with ADHD. *Am. J. Psychiatry* **162**, 1067–1075 (2005).
118. S. L. Hennessy, M. E. Sachs, B. Ilari, A. Habibi, Effects of music training on inhibitory control and associated neural networks in school-aged children: A longitudinal study. *Front. Neurosci.* **13**, 1080 (2019).
119. S. Jamadar, M. Hughes, W. R. Fulham, P. T. Michie, F. Karayanidis, The spatial and temporal dynamics of anticipatory preparation and response inhibition in task-switching. *Neuroimage* **51**, 432–449 (2010).
120. S. Klöppel *et al.*, The effect of handedness on cortical motor activation during simple bilateral movements. *Neuroimage* **34**, 274–280 (2007).
121. S. Koelsch, B. Maess, T. Grossmann, A. D. Friederici, Electric brain responses reveal gender differences in music processing. *Neuroreport* **14**, 709–713 (2003).
122. S. Arnold Anteraper *et al.*, Disrupted cerebrocerebellar intrinsic functional connectivity in young adults with high-functioning autism spectrum disorder: A data-driven, whole-brain, high-temporal resolution functional magnetic resonance imaging study. *Brain Connect.* **9**, 48–59 (2019).
123. S. Whitfield-Gabrieli *et al.*, Brain connectomics predict response to treatment in social anxiety disorder. *Mol. Psychiatry* **21**, 680–685 (2016).