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ABSTRACT

Learning disabilities are currently conceptualised as involving underlying weaknesses in cognitive processing, which has prompted growing interest in cognitive interventions that may alleviate learning challenges. One such programme , the Arrowsmith programme, targets a broad array of cognitive domains, but has not been evaluated. This study evaluated the cognitive and academic growth of students who participated in one academic year of the Arrowsmith programme and examined whether baseline MRI-derived myelin water fraction (MWF) and cognitive abilities were correlated with intervention outcomes. Participants demonstrated overall cognitive and academic growth as well as individual areas in which they improved after one year. Some areas of cognitive and academic growth were significantly correlated, suggesting a relationship in skill improvement. Baseline MWF and cognitive processing were related to higher or lower degrees of skill improvement in some areas. These results suggest that the Arrowsmith programme may be associated with improvements in cognitive and academic skills. In addition, they reflect the importance of considering individual characteristics at baseline when evaluating intervention outcomes.

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Introduction

Learning disabilities (LDs) are one of the most common disabilities identified in North American educational systems (Fletcher & de Lopez, 1995; Snyder, de Brey, Dillow, National Centre for Educational Statistics (ED), & American Institutes for Research (AIR), 2018). Current conceptualisations of LDs suggest that cognitive processing weaknesses contribute to developmental difficulty children can experience with learning (Hale et al., 2010). This conceptualisation is also evident in the definitions of many organisations, such as the Learning Disabilities Associations of Canada (LDAC) and America (LDA; LDA, n.d.; LDAC, n.d.). For example, these definitions refer to LD as involving a difficulty with information storing, processing, and/or production. In other words, cognitive processing is currently thought to underlie the academic struggles of children and youth with LD.

This conceptualisation is supported by data that identifies specific cognitive processes that are correlated with academic performance, that are weak in children and youth with LDs in these areas, and/or that correlate with the academic weaknesses of children and youth with LD. Some such cognitive processes include fluid reasoning, working and short-term memory, long-term memory, attention/vigilance, processing speed, verbal fluency, and auditory processing. Many of these processes are known to correlate well with achievement in general; for example, fluid reasoning correlates with maths and reading achievement (Caemmerer, Maddocks, Keith, & Reynolds, 2018; Cormier, McGrew, Bulut, & Funamoto, 2017). Working and short-term memory are also correlated with most aspects of academic achievement, and specific components of working memory – the phonological loop, visuospatial sketchpad, central executive, and episodic buffer – are linked to each academic domain as well (Costa, Green, Sideris, & Hooper, 2018; Shin & Pedrotty Bryant, 2015; Swanson, Olide, & Kong, 2018).

The cognitive processes of learning new information and retrieving it from long-term memory are also often associated with academic achievement, especially when it comes to academic fluency, such as the memorisation and retrieval of maths facts (Mussolin & Noël, 2008), and are known to be weak in students with maths learning disabilities (Shin & Pedrotty Bryant, 2015). General speed of processing as well as more specific aspects of focused attention, or vigilance, have been identified as areas of weakness for students with greater challenges in maths and have been related to the development of spelling and reading skills (Bar-Kochva & Nevo, 2019; Holm et al., 2018; Shin & Pedrotty Bryant, 2015). Verbal fluency, which combines elements of memory retrieval and processing speed, involves the rapid retrieval of vocabulary from a particular semantic category; this cognitive process, also known as retrieval fluency, has been linked to maths computation abilities (Villenueve, Hajovksy, Mason, & Lewno, 2018). Finally, auditory processing, and specifically the narrower cognitive ability of phonetic coding, plays a crucial role in the development of children's understanding of phonics and future decoding skills in reading. Unsurprisingly, these are identified as a frequent area of weakness in children with reading difficulties and dyslexia (Al Otaiba & Fuchs, 2002; Hämäläinen, Salminen, & Leppänen, 2012).

Neuroimaging literature provides additional support for the role of neurological and cognitive function (i.e., neurocognitive function) in the development of academic skills and in understanding the presentation of LD. This research points to the importance of functional connections between the neuroanatomical areas associated with language cognition and motor functioning in reading (Koyama et al., 2011), and demonstrates bilateral recruitment, particularly in the parietal and frontal cortices, during maths activities (Kaufmann, Wood, Rubinsten, & Henik, 2011). In children and youth with LD, differences in cognition and academic skill development can be further understood in light of neuroanatomical variance in the development of specific brain regions (Shaywitz et al., 2002; Simos et al., 2006), and in terms of functional connections between and within areas of the brain (Cao, Bitan, Chou, Burman, & Booth, 2006; Hoeft et al., 2007; Jobard, Crivello, & Tzourio-Mazoye, 2003). In general, children and youth with LD are found to have disrupted, altered, and/or less effective connections between crucial brain areas that form the neural networks supporting academic skill learning and demonstration. Studies that are specifically focused on the relationship(s) between white matter tracts and achievement or LD are limited, but suggest that, for maths learning, the left superior longitudinal fasciculus (SLF) and its connections with frontal cortex and both parietal and temporal cortex are of great importance (Jolles et al., 2016; Kucian et al., 2014; Tsang, Dougherty, Deutsch, Wandell, & Ben-Schachar, 2009; Van Beek, Gehsquiere, Lagae, & De Smedt, 2013). For reading, Vandermosten et al. (2012) proposed that the arcuate fasciculus (AF) and SLF comprise a dorsal route that involves decoding, and the inferior fronto-occipital fasciculus and inferior longitudinal fasciculus (ILF) comprise the ventral route that involves recognising regular and irregular words by their orthography. In children with dyslexia, white matter integrity is notably decreased compared to control groups, most notably in the left AF (Vandermosten, Boets, Wouters, & Ghesquiere 2012 ; Zhao, Thiebault de Schotten, Altarelli, Dubois, & Ramus, 2016).

Cognitive intervention

The focus on cognitive processing as a potential cause of learning challenge has resulted in a similar focus on cognitive intervention. Given that this cognitive intervention is prompted by a desire to improve academic achievement, cognitive intervention results are most commonly discussed in terms of their transfer, or the improvements they yield on skills that are not directly targeted by the intervention or programme. Transfer is understood as operating on a continuum, with "near" transfer being observed on intervention-targeted skills or exercises that are similar to those within a programme, and "far" transfer determined by related but different skill or exercises (Barnett & Ceci, 2002). Barnett and Ceci discuss multiple dimensions of tasks that should be used to determine their similarity to a programme's exercises. These include the knowledge being used in the task, the task's modality, and the physical, functional, and social contexts of the tasks.

For a task to be indicative of far transfer, Barnett and Ceci (2002) taxonomy would consider the knowledge domain an individual must access during the task, the physical setting in which they complete the task, when the task is completed, what social interactions are necessary to complete the task, and what aspects of functioning are involved in the task. Modality, like use of paper-and-pencil versus a computer, would also be taken into account. For cognitive interventions, such as those that intervene upon working memory (Melby-Lervåg, Redick, & Hulme, 2016), near transfer is commonly measured by tasks that also assess working memory but that are not identical to those used in the intervention itself. These are typically quite similar, per Barnett and Ceci (2002) taxonomy, in terms of knowledge domain, functional context, and modality, to name a few dimensions, to the exercises commonly used in these interventions. Far transfer, on the other hand, at least when it comes to recent evaluations of working memory interventions, is most frequently measured using academic tasks (Melby-Lervåg et al., 2016). Academic tasks, particularly in the context of an intervention, differ from working memory intervention exercises in a number of ways. They require the use of a different knowledge base (e.g., phonetic relationships, maths procedures, and spelling rules), typically involve a different temporal and physical context than the intervention (they are administered in a lab or clinic by people other than their interventionists, typically after the intervention has concluded), and they are more directly related to school functioning than a de-contextualised digit span task measuring working memory.

While several studies offer modest positive results (reviewed in Titz & Karbach, 2014), recent meta-analyses indicate that there is little evidence for the far transfer of cognitive training to academic skills, for children with learning difficulties as well as their typically developing peers (Diamond & Ling, 2016; Melby-Lervåg et al., 2016; Sala & Gobet, 2017). Of note, the majority of this research into cognitive training has been conducted on interventions that target working memory or other executive functions (Kassai, Futo, Demotrovics, & Takacs, 2019). Some studies that do show elements of far transfer, particularly to academics, involve important aspects of coaching and motivational support (Nelwan, Vissers, & Kroesbergen, 2018). Other recent findings suggest that certain cognitive processes, like fluid reasoning, may support transfer (Swanson & McMurran, 2018). In general, meta-analyses and literature reviews covering cognitive intervention programme describe the relationship between the duration of training and cognitive gains and a similar relationship between session length and cognitive gains, with both being a positive correlation (Diamond & Ling, 2016). In addition, more consistently challenging programme that enrol students with lower baseline skills also tend to produce the best results (Diamond & Ling, 2016).

The arrowsmith programme

The Arrowsmith programme is a somewhat novel approach compared to other recent cognitive intervention programme , in that it targets multiple cognitive processing weaknesses, with each student receiving an intervention plan comprised of multiple exercises, each focusing on a different process or combination of processes. No studies have yet been conducted to examine the effectiveness of this programme. The programme cognitive exercises, which were developed by Barbara Arrowsmith-Young (2012), include the following: *motor symbol sequencing*, which involves pen-and-paper and complex motor planning; *symbol relations*, which is a computer-based exercise involving conceptual relationships represented on an analogue clock; *memory for information or instructions*, an auditory exercise that involves unrelated information; *predicative speech*, another auditory exercise that involves sequential auditory information; *Broca's speech pronunciation*, which involves speech sound manipulations; *auditory speech discrimination*, which involves speech sounds in an unfamiliar language; *symbolic thinking*, a pen-and-paper exercise that involves language-based material; *symbol recognition*, a computer-based task involving symbolic meaning and memory; *lexical memory*, an auditory word memory exercise; *kinaesthetic perception*, involving drawing or writing with one's eyes closed; *quantification sense*, a computer-based exercise that requires continuous mental calculation; *nonverbal thinking*, a pen-and-paper exercise requiring interpretations of scenarios in pictures; *object recognition*, a computer-based exercise involving object sequences; and *spatial reasoning*, a pen-and-paper exercise involving following pathways within a spatial configuration. These exercises correspond to 19 areas of learning dysfunction, also developed by Arrowsmith-Young. Many share the names of the exercises, with additional areas of learning challenge including *kinaesthetic speech* (oral-motor awareness), *narrow visual span* (visual processing capacity), *mechanical reasoning* (understanding of machinery and tools), *abstract reasoning* (sequencing), and *primary motor* (muscular coordination). These exercises and their corresponding areas of learning dysfunction are also clearly related to the earlier discussed cognitive processes identified in recent cognitive and neuropsychology theory, such as long-term memory, working and short-term memory, and auditory processing. It is important to emphasise, however, that no empirical work has been conducted to link the exercises Arrowsmith-Young created, the areas of learning dysfunction she identified, and modern cognitive or neuropsychological theory. Based on theory only, it seems that at least 10 of the 13 exercises involve working and short-term memory processes, three target aspects of long-term memory, and six utilise auditory modalities. As mentioned, a student's yearlong participation in the Arrowsmith programme can involve multiple exercises and cognitive skill targets for improvement.

In addition to the novelty of its multiple cognitive targets, the Arrowsmith programme also differs from many other researched cognitive interventions in terms of its dosage. This programme's typical dosage is quite high, in that the typical student attends the Arrowsmith programme for 40 weeks over three-to-four years and completes at least 200 sessions each year, whereas some of the longest working memory interventions last 28 weeks, for 101 sessions (Melby-Lervåg et al., 2016). In addition, children and youth attend the Arrowsmith programme for the entire school day, with exercises dispersed throughout, whereas the working memory interventions included in Melby-Lervåg et al. (2016) meta-analysis involved sessions that lasted no longer than one-to-two hours. For these reasons, there may be cause to expect different outcomes in the Arrowsmith programme than have been observed in other cognitive intervention programmes.

The present study

As stated, the current research evaluated the preliminary results of a longitudinal study of the Arrowsmith programme, a cognitive intervention programme targeting children and youth with learning challenges, using neuroimaging and behavioural data. The Arrowsmith programme has not previously been evaluated, but it is important to note that these results are preliminary and so most analyses were exploratory. This study examined the following three research questions: (1) Do participants in the Arrowsmith programme experience cognitive and academic skill improvements after one year? (2) Do the skill improvements they experience in cognitive skills correlate significantly with those they experience in academic skills? (3) Does their baseline degree of myelination predict these skill improvements? Given the dosage and intensity of the Arrowsmith programme, cognitive changes after one year were expected, with particular expectations within those domains seemingly targeted by the programme (i.e., working and short-term memory, long-term memory, and auditory processing). It was unclear whether academic skill improvements would occur and whether any academic changes would be significantly correlated with cognitive changes in this sample. Finally, it was unclear to what extent baseline myelination would be correlated with the cognitive and academic intervention outcomes observed.

Method

Participants

A total of 28 children and youth (ages 9.5–16.8 years; M = 13.16 years; SD = 2.22 years) participated in this study during their first year of the Arrowsmith programme. The University clinical research ethics board approved this work. If participants were 14–-17 years old, they provided written informed consent; children between the ages of 9–-13 years provided assent and their parent of guardian consented to their participation. All ethical procedures were completed in accordance with the Declaration of Helsinki. The participants completed, on average, 9.2 (SD = 0.96) months of cognitive intervention. Participants were recruited through the Arrowsmith programme by sending out flyers to all families with enrolled children and youth. All children and youth participants were required to be between 9–17 years old and right-handed. Participants were excluded if they had a history of head trauma, a major psychiatric diagnosis, neurodegenerative disorder or substance abuse, were diagnosed with autism, or reported contraindications to MRI (e.g., had metal implants or piercing that could not be removed, braces or were claustrophobic). Additional demographic data are available in Table 1.

Table 1. Demographic and baseline data.

Variable	Mean (SD)
Age	13.16 years (2.22 years)
Time in Arrowsmith programme	9.2 months (0.96 months)
IQ	93.61 (18.04)
	N
Likely SLD in Reading	10
Likely SLD in Maths	17
Likely SLD in Writing	11
Likely Comorbid SLD in Reading and Maths	2
Low Achievement Across All Domains	9

Note. IQ = Intelligence Quotient as measured by the WJ-III NU COG General Intellectual Ability-Standard; SLD = Specific Learning Disorder

Instruments

Baseline and post-intervention testing included the *Woodcock-Johnson Third Edition Test of Cognitive Abilities, Normative Update* (WJ-III NU COG; McGrew, Schrank, & Woodcock, 2007) and the *Woodcock-Johnson Third Edition Test of Achievement, Normative Update* (WJ-III NU ACH; McGrew et al., 2007). The WJ-III NU COG and WJ-III NU ACH were individually administered by graduate research assistants. All participants underwent an MRI scan within two weeks of WJ-III NU COG and WJ-III NU ACH administration.

WJ-III NU COG

The WJ-III NU COG is an individually administered test of cognitive abilities that provides an overall estimate of intelligence as well as measurement of broad and narrow cognitive abilities. This instrument was standardised using a national sample of 8,782 subjects aged 2 through 90 years and older drawn from 100+ geographic regions of the United States and stratified to match the 2005 U.S. population (McGrew et al., 2007). The WJ-III NU COG is a psychometrically sound instrument and the reliability and validity indices of the selected tests used in this study are all within acceptable ranges (.80 or higher). It provides transformations of raw score data into test-specific W-scores that allow for tracking of student growth over time, as well as standard scores for normative comparisons. In this study, W-scores were used to track student growth in cognitive skill. Standard scores were also obtained to examine group comparisons to normative data. Tests from the WJ-III NU COG were used to measure skills in learning (Verbal-Auditory Learning), memory (Verbal-Auditory Learning Delayed), inductive reasoning (Concept Formation), processing speed (Decision Speed), working memory (Numbers Reversed), short-term memory (Memory for Words), auditory processing (Sound Blending), verbal fluency (Retrieval Fluency), and vigilance (Pair Cancellation).

WJ-III NU ACH

The WJ-III NU ACH is an individually administered test of academic achievement that provides an overall estimate of achievement as well as measurement of reading, maths, and writing abilities. This instrument was co-normed together with the WJ-III NU COG and provides well-established reliability and validity. The reliability and validity of selected tests used in this study are all within acceptable ranges (.80 or higher). Similar to the WJ-III NU COG, the WJ-III ACH also provides W-scores and standard scores, both of which were used in the present study. Tests from the WJ-III ACH were used to measure achievement in single-word reading (Letter-Word Identification), reading fluency (Sentence Reading Fluency), reading comprehension (Passage Comprehension), maths fact fluency (Maths Facts Fluency), maths computation (Calculation), maths problem solving (Applied Problems), and spelling (Spelling).

MRI acquisition

Magnetic resonance data were acquired at the University of British Columbia MRI Research Centre and were obtained on a Philips Achieva 3.0 T whole body MRI scanner (Phillips Healthcare, Best, NL) using an eight-channel sensitivity encoding head coil and parallel imaging. The following scans were collected: (1) 3D T1 turbo field echo (TFE) scan (TR = 7.4 ms, TE = 3.7 ms, flip angle $\theta = 6^\circ$ FOV = 256 × 256 mm, 160 slices, 1 mm slice thickness, scan time = 6.0 min) and (2) whole-cerebrum 32-echo three-dimensional gradient- and spin-echo (3D GRASE) for T2 measurement (TR = 1000 ms, echo times = 10, 20, 30, …, 320 ms, 20 slices acquired at 5 mm slice thickness, 40 slices reconstructed at 2.5 mm slice thickness (i.e., zero filled interpolation), slice oversampling factor = 1.3 (i.e., 26 slices were actually acquired but only the central 20 were reconstructed), in-plane voxel size = 1 × 1 mm, SENSE = 2, 232 × 192 matrix, receiver bandwidth = 188 kHz, axial orientation, and acquisition time = 14.4 min).

Myelin water fraction (MWF) analysis

All T1 scans were quality checked visually by a single rater using Freeview. Participants who showed markers of motion in the scanner on T1 scans were removed from the analysis. Four participants were removed due to motion in the scanner. A non-negative least-squares approach was used to partition the T2 signal into short (15-40ms), intermediate (40-200ms) and long (>1500ms) components for each voxel (Prasloski, Mädler, Xiang, MacKay, & Jones, 2012) using in-house software code (MATLAB R2010b, The MathWorks, Inc.) developed at the University of British Columbia. The myelin water fraction (MWF) was defined as the sum of amplitudes in the short T2 distribution divided by the sum of the amplitudes for the total T2 distribution. Voxel-based maps were produced for each participant to evaluate MWF in the desired regions of interest (ROI). The first echo of the 3D GRASE scan was co-registered to the T1 scan using FSL FLIRT (Jenkinson & Smith, 2001), and the acquired linear transformation matrix was used to register the MWF map to T1 space. Next, using FSL FNIRT (Jenkinson, Beckmann, Behrens, Woolrich, & Smith, 2012), the T1 scan was registered to Montreal Neurological Institute (MNI) space. The acquired non-linear transformation warp was then applied to the MWF map, bringing the MWF map to MNI space and allowing for application of the John Hopkins University (JHU) International Consortium of Brain Mapping (ICBM) DTI-81 white matter atlas (Mori et al., 2008). All regions of interest (ROIs) are identified in Figure 1. Mean MWF values from the following

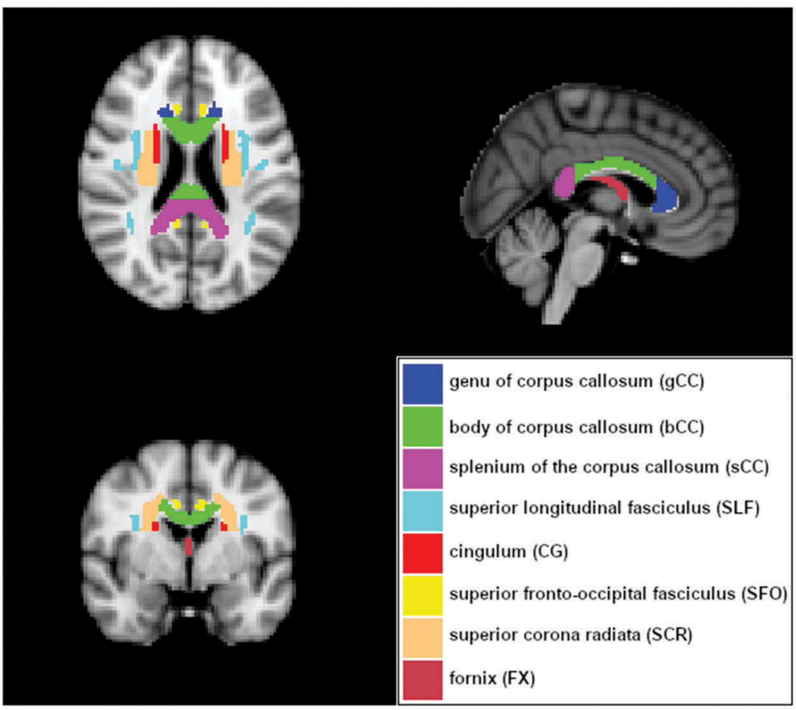

Figure 1. Two-dimensional presentation of the JHU ICBM-DTI-81 white matter atlas regions of interest (ROI) utilised in the myelin analysis.

JHU ICBM-DTI-81 white-matter atlas ROIs were extracted using FSL STATS: genu, body, and splenium of the corpus callosum (gCC, bCC, sCC), left and right superior longitudinal fasciculus (SLF-L, SLF-R), left and right cingulum (CG-L, CG-R), left and right superior fronto-occipital fasciculus (SFO-L, SFO-R), left and right superior corona radiata (SCR-L, SCR-R), and fornix (FX).

Procedures

Recruitment and data collection

All participants were recruited through the Arrowsmith programmes. Recruitment materials were distributed by Arrowsmith programme staff to incoming students and parents and students and their families opted to participate voluntarily by contacting the research team directly. Upon their volunteering, participants were invited to the university campus where neuroimaging and behavioural data were collected. WJ-III NU COG and ACH data were typically collected over two sessions, one of which included the neuroimaging protocol as well. Data were collected once when the participant initially volunteered and again after one calendar year.

Intervention

Students enrolled in the Arrowsmith programme attended this programme in a private school established for this programme for the entire school day, five days per week. Of note, they typically attend the Arrowsmith programme for three-to-four academic school years, with the current study evaluating only the first year of the programme. Each school day was divided into 40-minute periods, with students typically spending four periods per day on cognitive intervention tasks. As many as eight periods were available for these exercises. During periods when they were not engaging in cognitive exercises, students attended age-appropriate academic classes. Programming was individualised, in that each student's unique learning challenges were identified in one of the 19 areas and then targeted by the corresponding cognitive intervention exercises. Each exercise involved a task that increased in difficulty as students demonstrated mastery. For example, the *symbol relations* task involves quickly reading an analog clock, on which additional hands representing additional levels of time (e.g., the calendar date, milliseconds) are added as students master reading the clock hands at each level. Students are evaluated before attending the programme and at the end of each year of attendance in order to modify their programme as needed in the subsequent academic school year.

Analyses

First, sample characteristics, most notably in terms of their current intellectual (IQ) and academic development relative to the typically developing sample, were examined. Students with academic achievement consistent with a possible specific learning disorder per DSM-5 criteria (achievement in reading, maths, or spelling below a standard score of 85, or 1 standard deviation below the mean) were identified. Next, the cognitive and academic growth of the participants was examined, using repeated-measures MANOVA analyses and the W-scores for the WJ-III NU COG and ACH. Follow-up repeated-measures ANOVA analyses were also conducted. These analyses addressed Research

Question 1. To examine potential relationships between the cognitive and academic changes observed (addressing Research Question 2), the W-score changes in all cognitive and academic areas were correlated. Finally, the participants were divided into two groups, at the 50th percentile for the sample, based on their W-score change on each cognitive and academic test. These groups are referred to as demonstrating higher and lower levels of skill improvement. The myelin water fraction data were analysed using these two groups of participants, to address Research Question 3. Myelin water fraction is a histopathologically validated measure of myelin in the human brain (Laule et al., 2008). To examine potential effects of white matter structure on Arrowsmith programme response, baseline whole brain myelination and cognitive/academic growth were assessed using a series of one-way ANOVAs. These tests were run with the dichotomous skill improvement variable as the grouping factor and baseline whole brain mean MWF value as the dependent variable. Next, to examine if myelination of specific ROIs was associated with cognitive/academic growth in the context of the Arrowsmith programme, a series of one-way ANOVAs were run with the dichotomous skill improvement variables as the grouping factor using extracted ROI mean MWF values as dependent variables. Regions of interest were selected a priori; these choices were motivated by the existing literature (Bennett, Madden, Vaidya, Howard, & Howard, 2011; Charlton, Barrick, Lawes, Markus, & Morris, 2010; Chiang, Chen, Lo, Tseng, & Gau, 2015; Chopra et al., 2018).

Results

Sample characteristics

The mean sample IQ mean was 93.61 (SD = 18.04), which is within the Average range of performance (McGrew et al., 2007). As a sample, the group also demonstrated Average (Standard Score = 90–109) single word reading, reading fluency, spelling, written expression, decoding, and maths problem solving skills. Their maths fluency (M = 87.89, SD = 17.74), reading comprehension (M = 89.00, SD = 16.15), and maths computation (M = 86.54, SD = 19.73) were in the Low Average range of performance (McGrew et al., 2007). Thirteen of the participants (46.4%) performed poorly (below a standard score of 85, lower than one standard deviation below the mean) on at least one measure of reading, suggesting a possible specific learning disorder or challenge in this area. Seventeen (60.7%) of the participants performed poorly (below a standard score of 85) on one measure of maths, suggesting a possible specific learning disorder or challenge in this area. Eleven of the participants (39.3%) performed poorly on at least one measure of writing (below a standard score of 85). Nine of the participants (32.1%) had no identified learning challenges in reading, maths, or writing. Nine (32.1%) had learning challenges in all three academic domains, five (17.9%) had only maths challenges, and two (7.1%) had maths and reading challenges. One participant had writing and maths challenges, one had literacy (reading and writing) challenges, and one had only reading challenges.

Cognitive skill improvement

A repeated-measures MANOVA analysis was used to determine if cognitive skill improvement occurred across all cognitive domains. Follow-up univariate analyses with Bonferroni corrections were also conducted. W-scores were used for all cognitive domains assessed. A significant multivariate effect was found for time (Wilk's λ = .11, F (9, 17) = 15.61, $p < .001$, $\eta_p^2 = .89$). This is consistent with a large effect (Cohen, 1988). Univariate effects were found for time in the domains of learning (Verbal-Auditory Learning), memory (Verbal-Auditory Learning Delayed), verbal fluency (Retrieval Fluency), inductive reasoning (Concept Formation), processing speed (Decision Speed), and vigilance (Pair Cancellation). Univariate effect sizes ranged from small (.18) to moderate (.58; Cohen, 1988) All cognitive skill univariate statistics are available in Table 3. The sample's mean change in cognitive W-scores over time ranged from −1.00 (working memory; SD = 20.22) W-score points to +13.93 (vigilance; SD = 11.90) W-score points. All cognitive data at baseline and post-test are available in Table 2.

Academic skill improvement

A repeated-measures MANOVA analysis was also used to determine if academic skill improvement occurred across all academic achievement areas. Follow-up univariate analyses with Bonferroni corrections were conducted and W-scores were used for all achievement areas. A significant multivariate effect was found for time (Wilk's λ = .36, F (7, 21) = 5.46, $p < .01$, $\eta_p^2 = .65$). This is consistent with a moderate effect (Cohen, 1988). Univariate effects were found for time in the achievement areas of single-word reading, reading fluency, maths fluency, computation, and spelling. These effect sizes ranged from small (.14) to moderate (.54) in size (Cohen, 1988). All academic skill

Table 2. Cognitive and academic performance data (Standard scores).

	Mean (SD)	
Variable	Baseline	Post-test
IQ	93.61 (18.04)	96.78 (18.08)
Learning	82.30 (14.26)	90.59 (17.57)
Long-term Memory	86.22 (17.41)	89.96 (17.94)
Auditory Processing	105.71 (16.33)	108.48 (18.20)
Inductive Reasoning	95.21 (19.91)	102.00 (16.35)
Processing Speed	93.29 (22.73)	104.15 (19.24)
Working Memory	91.14 (18.05)	91.07 (21.34)
Short-term Memory	94.50 (12.51)	100.30 (13.38)
Verbal Fluency	94.57 (19.89)	96.93 (14.42)
Vigilance	94.96 (12.94)	104.58 (13.32)
Single-word Identification	97.82 (18.33)	97.44 (19.96)
Reading Fluency	92.75 (20.26)	97.59 (23.32)
Reading Comprehension	89.00 (16.15)	88.63 (18.62)
Computation	86.54 (19.73)	89.33 (22.70)
Maths Fluency	87.89 (17.74)	94.19 (18.37)
Maths Problem-solving	93.54 (17.59)	91.81 (20.82)
Spelling	96.82 (22.82)	99.63 (30.28)

Note. IQ = Intelligence Quotient; Learning = Verbal-Auditory Learning Test; Long-term Memory = Verbal-Auditory Learning Delayed Test; Auditory Processing = Sound Blending Test; Inductive Reasoning = Concept Formation Test; Processing Speed = Decision Speed Test; Working Memory = Numbers Reversed Test; Short-term Memory = Memory for Words test; Verbal Fluency = Retrieval Fluency test; Vigilance = Pair Cancellation Test; Single-word Identification = Letter-word Identification Test; Reading Fluency = Sentence Reading Fluency Test; Reading Comprehension = Passage Comprehension Test; Computation = Calculation Test; Maths Fluency = Maths Fluency Test; Maths Problem-Solving = Applied Problems Test; Spelling = Spelling Test

Table 3. Univariate results for time in cognitive data.

Variable	Sum of Squares	F	*p*	η_p^2
Learning	366.23	19.41	.00	.44
Long-term Memory	123.08	5.55	.03	.18
Verbal Fluency	35.56	6.84	.02	.22
Auditory Processing	108.17	2.49	.13	.09
Inductive Reasoning	510.94	7.03	.01	.22
Processing Speed	964.92	27.16	.00	.52
Vigilance	2275.69	34.06	.00	.58
Working Memory	.31	.00	.97	.00
Short-term Memory	398.77	1.67	.21	.06

Note. Learning = Verbal-Auditory Learning Test; Long-term Memory = Verbal-Auditory Learning Delayed Test; Auditory Processing = Sound Blending Test; Inductive Reasoning = Concept Formation Test; Processing Speed = Decision Speed Test; Working Memory = Numbers Reversed Test; Short-term Memory = Memory for Words test; Verbal Fluency = Retrieval Fluency test; Vigilance = Pair Cancellation Test.

Table 4. Univariate results for time in academic data.

Variable	Sum of Squares	F	*p*	η_p^2
Single-word Identification	265.79	5.91	.02	.18
Reading Fluency	928.29	31.22	.00	.54
Reading Comprehension	105.88	3.67	.07	.12
Computation	637.88	16.35	.00	.38
Maths Fluency	301.79	25.45	.00	.49
Maths Problem-solving	27.16	.26	.61	.01
Spelling	196.88	4.55	.04	.14

Note. Single-word Identification = Letter-word Identification Test; Reading Fluency = Sentence Reading Fluency Test; Reading Comprehension = Passage Comprehension Test; Computation = Calculation Test; Maths Fluency = Maths Fluency Test; Maths Problem-Solving = Applied Problems Test; Spelling = Spelling Test.

univariate statistics are available in Table 4. The sample's mean change in academic W-scores over time ranged from +1.39 (maths problem solving; SD = 14.42) to +8.14 (reading fluency; SD = 7.71) W-score points. All achievement data at baseline and post-test are available in Table 2.

Relationship between cognitive and academic skill improvement

Bivariate correlational analyses were run to determine the relationship between the cognitive and academic skill improvement experienced by the sample. First, W-score change variables were computed for each cognitive and academic domain and then correlational analyses were conducted. Improvement in single-word reading, reading fluency, spelling and computation were not associated with any cognitive skill growth. Improvement in reading comprehension was associated with growth in auditory working memory span (echoing words; $r = .38$; $p < .05$). Improvement in maths fluency was associated with cognitive improvement in auditory processing (phonetic coding; $r = .40$; $p < .05$) and vigilance ($r = .47$; $p < .05$). Improvement in maths problem solving was associated with cognitive growth in inductive reasoning ($r = .47$; $p < .05$).

Skill improvement and brain structure

Groups of participants with higher and lower skill improvement in each cognitive and academic domain were created by dividing the group above and below the 50th percentile for W-change score in each domain. This created 16 sets of two groups, with each group containing between 11 and 17 participants. At baseline, there were some cognitive differences between the participants who experienced higher or lower skill improvement in certain domains. No baseline differences were observed in academic skill improvement groupings. For long-term memory skill improvements, the higher skill improvement group started the intervention with stronger verbal fluency at baseline (F (1, 23) = 5.45, p < .05, η_p^2 = .19). Participants who experienced greater skill improvement in auditory processing were stronger at baseline in terms of their inductive reasoning (F (1, 23) = 7.85, p < .05, η_p^2 = .25) and learning (F (1, 23) = 13.48, p < .01, η_p^2 = .37). Finally, but in contrast, participants in the group with higher processing speed improvement demonstrated weaker working memory (F (1, 23) = 5.09, p < .05, η_p^2 = .87) and long-term memory (F (1, 23) = 4.30, p = .05, η_p^2 = .16) at baseline.

There were no significant differences in baseline whole brain MWF values between participants with high and low skill improvement in any of the selected cognitive domains or academic areas. As mentioned, regions of interest were selected *a priori*. Those who showed greater skill improvement in working memory showed significantly greater baseline MWF values in the following brain areas: Callosum (gCC (F[1,22] = 5.61, p = .027), bCC (F [1,22] = 5.90, p = .024)); Superior longitudinal fasciculus (SLF-L (F[1,22] = 4.36, p = .049), SLF-R (F[1,22] = 9.81, p = .005)); Corona radiata (SCR-R (F[1,22] = 7.29, p = .013)); Superior fronto-occipital fasciculus ((SFO-L (F[1,22] = 9.76, p = .005), SFO-R (F[1,22] = 4.90, p = .038), CG-L (F[1,22] = 6.04, p = .022)); and Cingulum (CG-R (F[1,22] = 4.63, p = .043); Figure 2). Those who showed greater skill improvement in vigilance showed significantly greater baseline MWF values in SLF-L (F [1,22] = 4.69, p = .042), SLF-R (F [1,22] = 6.94, p = .015), SCR-R (F [1,22] = 4.56, p = .044), and SFO-R (F [1,22] = 8.48, p = .008; Figure 3). Baseline MWF values in extracted ROIs did not show significant differences between skill improvement groups on any of the other cognitive domains or any achievement area.

Discussion

This study was the first to evaluate any outcomes associated with the Arrowsmith programme, though these results should be considered preliminary. The current research examined the cognitive and academic skill improvement in children and youth who completed one academic year in the Arrowsmith programme (9–10 months). Longitudinal improvements in academic skill were correlated with measures of cognitive functioning taken at baseline before students entered the Arrowsmith programme. Those with higher baseline cognitive functioning showed greatest improvement. Similarly, baseline degree of brain myelination also correlated with improvements in academic skill, such that those with higher baseline myelination showed greater improvements across time. Twenty-eight Arrowsmith students were evaluated using behavioural measures of cognitive and academic development and MRI-derived myelin water fraction (MWF) data. The cognitive and academic data were used to determine skill improvement across the sample as well as to determine whether cognitive skill growth was correlated

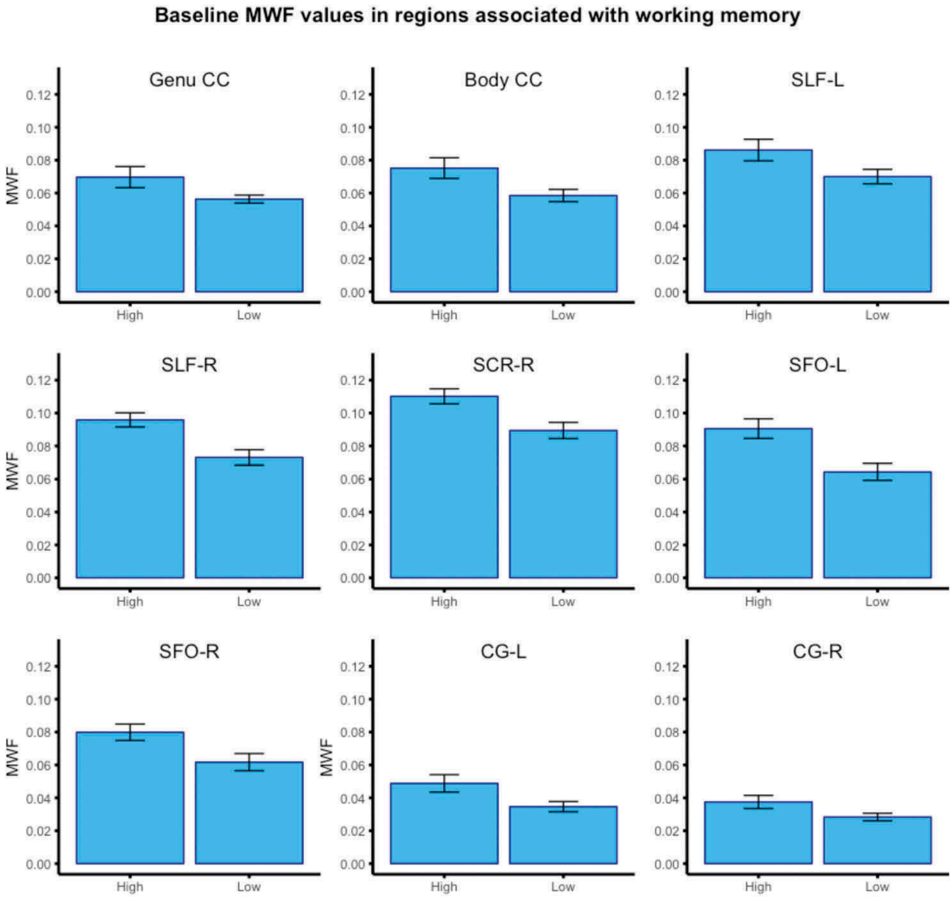

Figure 2. *a priori* selected ROIs with significant differences in baseline MWF values ($p < .05$) between participants who showed higher or lower WJ-III NU COG working memory improvements after one year in the Arrowsmith programme.

with observed academic skill growth. Of note, all students enrolled in the Arrowsmith programme had a history of learning challenges that prompted their enrolment, though approximately one-third of this sample did not perform below normative expectations at baseline in any academic domain. The remaining 68% of the participants (N = 19) performed below age expectations on at least one measure of reading, writing, or maths.

While these analyses were primarily exploratory in nature, it was expected the students would experience cognitive skill improvement after their participation in the Arrowsmith programme. This growth was observed in general in terms of a significant and large multivariate effect, and specifically in terms of learning, long-term memory, verbal fluency, inductive reasoning, processing speed, and vigilance (attention). These results represent evidence of possible near transfer. Surprisingly, no significant cognitive improvement was observed in the group in terms of auditory processing or working memory, though these cognitive domains are involved in multiple Arrowsmith exercises (at least 6 and 10, respectively).

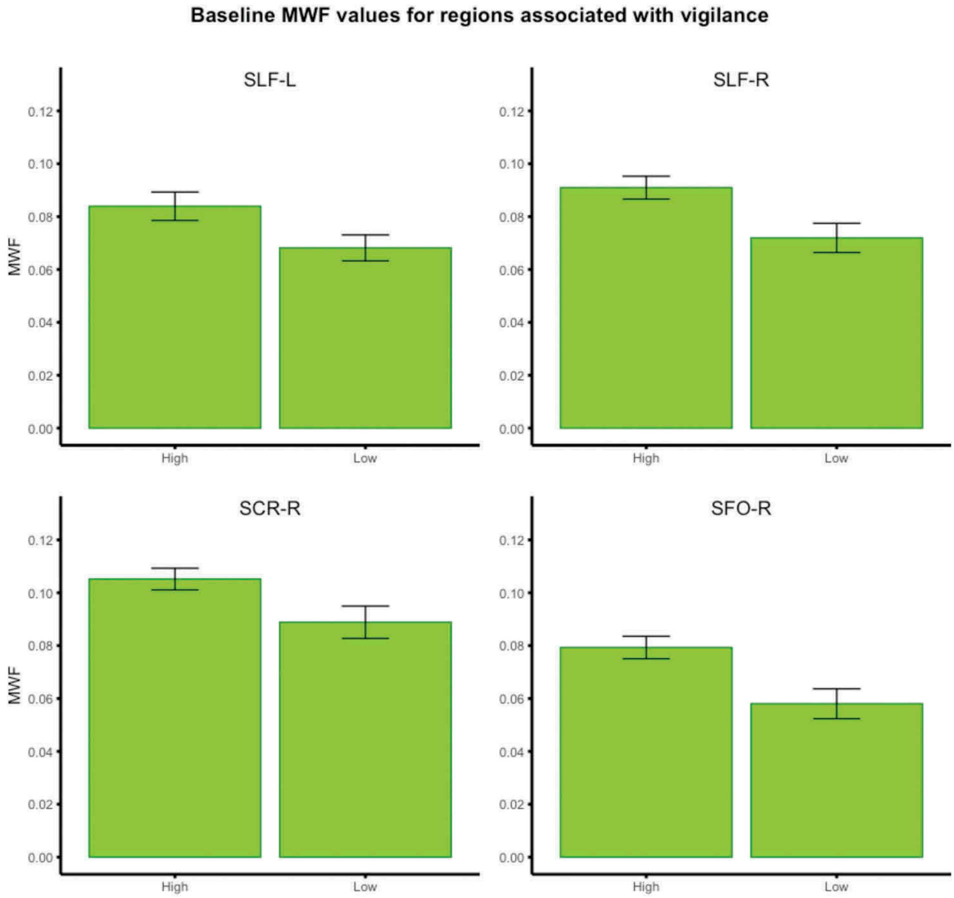

Figure 3. *a priori* selected ROIs with significant differences in baseline MWF values ($p < .05$) between participants who showed higher or lower WJ-III NU COG vigilance improvements after one year in the Arrowsmith programme.

It was unclear whether academic skill improvement would be observed in this sample, given the failure of most cognitive interventions to produce far transfer effects, but nonetheless a significant, moderate multivariate effect was observed, indicating overall academic skill improvement across participants. This effect was followed by univariate effects in single-word reading, reading fluency, maths fluency, computation, and spelling, though these effects ranged in size from fairly negligible to moderate. To further examine this potential transfer, the cognitive and academic skill improvement in this sample were correlated with one another. Interestingly, some areas of cognitive growth that were not significantly changed over time were significantly correlated with areas of academic skill improvement. In addition, some areas of academic skill improvement that were not significantly changed over time were significantly correlated with areas of cognitive improvement. Of the significant correlations, the only related domains that were also significant areas of improvement for the sample were maths fluency and vigilance. These two areas were moderately correlated, and this finding is consistent with previous research that correlates attention with maths fact fluency performance (Ackerman, Anhalt, Holcomb, & Dykman, 1986; Gold et al., 2013; Zentall, 1990). In addition, while maths problem solving was not an area of growth for the whole sample, the finding of a significant correlation between inductive reasoning growth and maths problem solving growth is consistent with previous findings related to the role of fluid reasoning in far transfer (Swanson & McMurran, 2018).

The binarizing of participants as higher and lower responders in terms of academic skill improvements and subsequent finding that higher responders showed significantly higher baseline cognitive function and baseline myelination allows us to speculate on potential cognitive and neurobiological mechanisms underlying response to the Arrowsmith programme. First, it seems that some aspects of cognitive processing can be leveraged, or may even be necessary, in order to experience cognitive improvement in the Arrowsmith programme. In this study, aspects of verbal fluency, inductive reasoning, and learning were stronger at baseline in individuals who later experienced more skill growth in other areas. Interestingly, these baseline behavioural differences did not correspond to differences in baseline myelination between the two skill improvement groups. In contrast, individuals who experienced greater growth in processing speed actually had worse working memory and long-term memory prior to the intervention. This finding is the most consistent with previous literature, which suggests that individuals with the poorest skills often experience the greatest gains in cognitive interventions (Diamond & Ling, 2016). In terms of the former findings, more research is needed to investigate how verbal fluency may support long-term memory improvement and how reasoning and learning skills can be leveraged for growth in auditory processing.

No significant differences were found between those experiencing lower and higher skill improvement in any cognitive domain in terms of whole brain myelination. In addition, skill improvement in two cognitive domains was related to baseline myelination in several regions of interest, but these also did not correspond to the behavioural findings. Participants who experienced greater working memory growth also tended to demonstrate greater baseline myelination in several regions of interest, including the corpus callosum, superior longitudinal fasciculus (SLF), corona radiata, superior fronto-occipital fasciculus (SFOF), and cingulum. These results are consistent with what is known about the working memory neural network, which spans a large number of regions including the prefrontal cortex, inferior and superior parietal lobe, medial temporal lobe, and sensory cortices (Lazar, 2017). This widespread network requires multiple white matter pathways in order to process information efficiently. These findings contribute to a fairly scarce literature base that relates white matter integrity to working memory capacity (Darki & Klingberg, 2015), and even more specifically, capacity to benefit from cognitive intervention in this domain. In addition, this study demonstrates these findings within a population with learning challenges, as opposed to previous studies that have used typically developing children and youth. Participants who experienced greater growth in vigilance also tended to demonstrate greater baseline myelination in the SLF, corona radiata, and SFOF. Previous literature points to the role of the parietal cortex in attention-based tasks, and the importance of the SLF in connecting the frontal, parietal, and temporal cortices in an attention network (Chiang et al., 2015; Klarborg et al., 2013; Thakral & Slotnick, 2009). Neurobiologically, it may be the case that greater myelination in this network at baseline allowed for faster signal transduction between regions associated with these working memory and attention networks, improving efficiency of the networks by giving responders more neural substrate to leverage, ultimately delivering a stronger baseline platform from which to improve cognition . Alternatively, higher MWF values could simply reflect a more mature brain capable of dealing with greater cognitive demands.

Cognitive skill improvement

This study represents preliminary evidence of the cognitive outcomes associated with participation in one academic year of the Arrowsmith programme. As mentioned, this programme is usually attended for three to four years, meaning this would not represent the final growth expected in a typically enrolled student. In addition, given the use of W-scores and the absence of a control group, it is not yet clear if the observed cognitive improvement represents what would be expected in typical development or whether it is greater than would be observed in other specialised education programmes. The Arrowsmith programme targets a wide array of cognitive domains, including each of the cognitive domains investigated in this study. The significant multivariate effect that emerged is consistent with this broad targeting of multiple cognitive skills, and suggests that, overall, the students in this programme improved over the course of their year relative to their own baselines. In addition, they improved in several areas of cognition that are known targets of the programme. It is unclear why the group did not demonstrate improvement in working memory, especially given the number of Arrowsmith exercises (at least 10) that seem to address this skill area.

There are several possible reasons why a significant univariate effect was not found in the domain of working memory. The first could be the way in which it was measured, using an auditory span and manipulation task (WJ-III NU COG Numbers Reversed). Given that the Arrowsmith programme addresses a wider array of working memory skills, it is possible that this measure was too narrow or perhaps even too easy (or too difficult) to capture the working memory improvements following this intervention. The second possibility could be related to the analyses run and the additional findings related to working memory response and white matter integrity. It is possible that, due to a strong reliance on the integrity of the white matter neural networks associated with working memory, working memory growth was not observed across the entire sample, but instead only in those with the necessary capacity. Finally, it is possible that the whole sample did not improve on this skill because of the individualised nature of the Arrowsmith programme, meaning some participants' intervention plans did not target this domain. Future research regarding the role of individual differences, including baseline white matter integrity, in explaining Arrowsmith programme response in working memory is warranted based on these results.

It is also unclear why cognitive improvements were not observed in auditory processing. Fewer Arrowsmith exercises target this cognitive domain than working memory, but it is still involved in at least six of them. It is possible that fewer participants' intervention plans were targeting this area and that this contributed to the lack of significant findings on the WJ-III NU COG Sound Blending test. Similar to the working memory results, it is also possible that this test does not represent the true skill target of the Arrowsmith intervention.

Academic skill improvement

It is encouraging that the Arrowsmith programme participants improved in their academic skills, particularly as they typically receive very little academic-focused instruction during their first year in the programme (e.g., less than half of a school day). Similar to the cognitive results, however, it is important to note that it is not yet clear if the academic growth observed is greater than (or even equal to) what would be observed in development or other programming. The academic improvements observed in this study suggest improvements in the fundamental skills associated with reading, writing, and mathematics, and with increased automaticity, or fluency. They do not provide evidence of improvement in the application of academics, or in higher-order achievement skills like reading comprehension, maths problem-solving, and written composition. The skills improved in this sample represent the building blocks that support higher-order academic abilities, though, and it is possible that improvements in future years may include these areas of achievement as well. Given the lack of evidence of far transfer in the literature on cognitive intervention (Melby-Lervåg et al., 2016; Sala & Gobet, 2017), it will be crucial that these results lead to further evaluation of any academic growth observed in Arrowsmith participants. In addition, future comparisons should be made between the transfer effects of the Arrowsmith programme and other cognitive programmes.

White matter and skill improvement

White matter integrity has been found to relate to intervention response in a number of areas, including pharmacological response to antipsychotic medication (Reis Marques et al., 2014) and language training (Meinzer et al., 2010), but is generally under-researched. As mentioned, these results indicate that individual differences at baseline likely correlate with cognitive improvement within the Arrowsmith programme. These findings will inform future research that not only seeks to confirm whether the growth observed in this study is unique to the programme but also identifies what other individual characteristics seem to prime an individual to benefit most from this intervention.

These findings also suggest the involvement of white matter tracts that are not often associated with working memory and vigilance/attention in the research literature. The available data seem to be mixed in terms of the cingulum bundle. For example, cingulum white matter integrity has been correlated with processing speed/reaction time and spatial intelligence in recent research, but not necessarily with working memory span or manipulation accuracy (Tang et al., 2010; Wilde et al., 2010). Nonetheless, the cingulate gyrus is known to be crucial in several aspects of cognitive control (Miller & Cohen, 2001; Paus, Petrides, Evans, & Meyer, 1993). For example, damage to white matter connecting the prefrontal cortex and cingulate gyrus is suggested to account for many of the neurocognitive difficulties encountered by individuals with traumatic brain injuries (TBI; Azouvi, 2000). The TBI population, as well as other populations such as attention-deficit/hyperactivity disorder (ADHD) and those with agenesis of the corpus callosum, also provide relevant literature for the current neuroimaging findings regarding the corona radiata, SFOF, and corpus callosum (Palacios et al., 2012; Siffredi et al., 2017; van Ewijk, Heslenfeld, Zwiers, Buitelaar, & Oosterlaan, 2012).

Limitations

The limitations of the interpretation of these findings as representing true, unique improvements caused by the Arrowsmith programme have already been discussed. Such claims cannot be made without adequate control group comparisons. In addition, these claims cannot be made without significantly more Arrowsmith participants (i.e., a larger sample size in general) and additional years of longitudinal data that better represent the full, typical programme. The neuroimaging analyses may have been limited by the fact that the MNI standard space and white mater atlas used were developed for adult brains. This may have limited the findings here given that our sample only included children and youth, but it should be noted that there are currently no paediatric specific atlases based on myelin data.

Conclusions

The findings from this paper yield promise for the potential growth children and youth may experience as a result of participation in the Arrowsmith programme. These results should be also be viewed as demonstrating the need for an examination of responsiveness to cognitive and academic intervention, including the Arrowsmith programme, in light of individual characteristics and skills.

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