Dorsal visual stream activity during coherent motion processing is not related to math ability or dyscalculia

Marissa L. Laws[1,2], Anna A. Matejko[1], Melanie Lozano[1], Eileen Napoliello[1], Guinevere F. Eden[1,2]

[1]Center for the Study of Learning, Department of Pediatrics, and [2]Interdisciplinary Program in Neuroscience, Georgetown University Medical Center, Washington DC

Corresponding Author:

Guinevere Eden, D.Phil.
Center for the Study of Learning
Georgetown University Medical Center
BOX 571406
Suite 150, Building D
4000 Reservoir Rd, NW
Washington DC 20057
edeng@georgetown.edu

Abstract

Math disability (MD) or developmental dyscalculia is a highly prevalent learning disability involving deficits in computation and arithmetic fact retrieval, and is associated with dysfunction of parietal and prefrontal cortices. It has been suggested that dyscalculia (and other learning disabilities and developmental disorders) can be viewed in terms of a broader ‘dorsal stream vulnerability,’ which could explain a range of dorsal visual stream function deficits, including poor coherent visual motion perception. Behavioral evidence from two studies in typical children has linked performance on visual motion perception to math ability, and a third behavioral study reported poorer visual motion perception in a small group of children with MD compared to controls. Visual motion perception relies on the magnocellular-dominated dorsal stream, particularly its constituent area V5/MT. Here we used functional MRI to measure brain activity in area V5/MT during coherent visual motion processing to test its relationship with math ability. While we found bilateral activation in V5/MT in 66 children/adolescents with varied math abilities, we found no relationships between V5/MT activity and standardized math measures. Next, we selected a group of children/adolescents with MD (n=23) and compared them to typically developing controls (n=18), but found no differences in activity in V5/MT or elsewhere in the brain. We followed these frequentist statistics with Bayesian analyses, which favored null models in both studies. We conclude that dorsal stream function subserving visual motion processing in area V5/MT is not related to math ability, nor is it altered in those with the math disability dyscalculia.

Highlights

- We measured activity during visual motion perception and performance on math tasks
- There was no relationship between V5/MT activity and math in children/adolescents
- We found no anomalies in V5/MT activity in those with math disability/dyscalculia
- Bayesian analyses in both studies favored null models
- We conclude that dorsal stream function in area V5/MT is not related to math ability

Keywords

dyscalculia, math disability, coherent motion, dorsal visual stream, fMRI, V5/MT

1. Introduction

The math disability (MD) developmental dyscalculia is characterized by deficits in fluent and accurate computation and arithmetic fact retrieval, despite adequate intelligence and instruction (American Psychiatric Association, 2013). Occurring in an estimated 6% of individuals, MD is thought to be caused by poor number sense, defined as the ability to represent and manipulate approximate or discrete numerical magnitudes (Butterworth, 2010; Piazza et al., 2010; Wilson et al., 2015), which is then thought to give rise to difficulties learning and retrieving arithmetic facts from long-term memory (De Smedt et al., 2013; Geary et al., 2009; Peters & De Smedt, 2018). These "core deficits" may be complemented by other domain-general cognitive impairments, such as in working memory (especially visuospatial working memory), attention, or language ability, suggesting a multicomponent framework of MD may be more accurate (Ashkenazi et al., 2013b; Fias et al., 2013; Geary et al., 2009; Slot et al., 2016; for a review, see Iuculano, 2016). Functional neuroimaging studies examining brain activation during fact retrieval and magnitude processing tasks have shown differences in those with MD compared to controls, usually in bilateral parietal and/or inferior frontal cortices (Ashkenazi et al., 2012; Davis et al., 2009; Kucian et al., 2006; Price et al., 2007; Rosenberg-Lee et al., 2015; for reviews, see Ashkenazi et al., 2013a; Peters & De Smedt, 2018).

It has also been suggested that MD could be conceptualized in a broader "dorsal stream vulnerability" framework (Atkinson, 2017; Braddick et al., 2003). This framework focuses on the differentiation of the dorsal cortical stream ("where" pathway, for recognizing where objects are in space) from the ventral cortical stream ("what" pathway, for the recognition of objects) (De Yoe & Van Essen, 1988; Ungerleider & Mishkin, 1982). Specifically, it is thought that the relatively longer timespan for dorsal stream development compared to ventral stream development renders the dorsal stream more susceptible to impairment (Braddick et al., 2003). Braddick and colleagues (2003) describe children with a range of neurodevelopmental disorders such as Williams Syndrome, (congenital) hemiplegia, autism, and developmental dyslexia, in whom deficits in dorsal visual stream function have been observed, including impairments to coherent motion sensitivity, visuospatial cognition, attention, and visuomotor control. At the same time, functions of the ventral visual stream such as processing of visual form are spared in these disorders. Based on this, behavioral measures of coherent visual motion sensitivity (relative to form sensitivity) have been used by Braddick and colleagues as a "specific and sensitive indicator of brain development" and to characterize overall dorsal visual stream integrity in children (Braddick et al., 2003; Braddick et al., 2016). Braddick et al. (2016) also described math disability as one of the disorders that can be explained by their dorsal stream vulnerability model, and that behavioral measures of coherent visual motion sensitivity should therefore be related to math performance.

Such a relationship between performance on coherent motion detection and math ability in typically developing children has been reported in two behavioral studies. Boets and colleagues (2011) showed in a longitudinal study that individual differences in coherent motion sensitivity in kindergarten correlated with later speed of subtraction (in third grade). The effect was specific to subtraction; no such relationship was found for multiplication. The dorsal stream is thought to facilitate procedural computations used to solve subtraction, but it is not associated with the verbally-based retrieval likely used during multiplication (Barrouillet et al., 2008; Campbell & Xue, 2001; Dehaene et al., 2003; Prado et al., 2014). The authors therefore concluded that coherent motion detection is associated with procedural math learning due to their mutual reliance on the dorsal cortical pathway, and that the longitudinal nature of the relationship suggests that low-level visual mechanisms used for coherent motion processing may constrain later development of numerical skills. They did not, however, find a correlation between the children's coherent motion sensitivity in kindergarten and *accuracy* of subtraction in third grade, thereby not fully supporting this longitudinal relationship. Further, evidence from Braddick and colleagues (2016) indicates that greater coherent motion sensitivity is concurrently related with better performance on math achievement measures (calculation and word problems), as well as better number sense (numerosity judgments), in children aged 5-12yrs. The same study also examined brain structure, and found that greater parietal lobe surface area was associated with greater coherent motion sensitivity. They did not, however, find a correlation between parietal lobe surface area and measures of math or number sense. The authors interpreted their results as evidence that coherent motion performance, as a signature of dorsal stream function, is directly associated with math skills and is a sensitive indicator of individuals' math development. While they suggest that there is a relationship between underlying dorsal stream anatomy and both visual motion perception and math skills, ultimately, there was no evidence that neuroanatomy of the dorsal stream was related to math skills. As such, the question remains whether the brain's integrity in the dorsal visual stream is related to math ability.

Turning to children with impaired math skills, a behavioral study by Sigmundsson, Anholt, & Talcott (2010) found that 10-11 year-olds with low math achievement performed significantly worse in coherent visual motion perception than an age-matched group with high math achievement. The authors also suggested that this deficit in sensitivity for visual motion perception may represent a common underlying risk factor for many developmental disabilities. However, the sample size used in the study was small (six children per group), and children were not characterized in terms of comorbid learning disability or Attention Deficit/Hyperactivity Disorder, thereby providing only limited evidence for impaired visual motion processing in children with MD specifically.

Taken together, these behavioral studies suggest that coherent motion sensitivity may relate to math ability in typically developing children, and that children with MD perform worse than controls on coherent motion detection tasks. However, it is important to confirm that brain function underlying coherent visual motion processing is indeed affected in MD, if this measure is to serve as a marker for the other dorsal stream dysfunction associated with MD. Specifically, we ask the question, does activity in the dorsal visual stream during coherent motion processing relate to math skills, and are there functional anomalies in the dorsal visual stream during coherent motion processing in children with MD in support of this framework? Neuroimaging studies have often shown abnormal brain activity in the parietal cortex during arithmetic tasks in children with MD compared to controls (Ashkenazi et al., 2012; Davis et al., 2009; Kucian et al., 2006; Rosenberg-Lee et al., 2015). It is not known, however, whether children with MD show anomalies in the earlier dorsal visual stream area V5/MT, the hub of visual motion perception (McKeefry et al., 1997; Sunaert et al., 1999; Tootell et al., 1995; Watson et al., 1993; Zeki et al., 1991). Assessing brain activity during coherent motion processing is a first step towards determining whether the parietal anomalies in MD represent a specific deficit, or if there are other dorsal stream function aberrations, specifically during visual motion perception.

In the present study, we measured brain activity with functional magnetic resonance imaging (fMRI) during a coherent visual motion detection task to test whether activity in area V5/MT, the primary cortical motion-processing region of the dorsal visual stream, relates to math ability. We used two complementary approaches to build on the above-described studies that have assessed continuous relationships between visual motion detection and math ability (Boets et al., 2011; Braddick et al., 2016) or assessed group differences between children with and without MD (Sigmundsson et al., 2010). In Study 1, we used regression analyses to test for brain-behavior relationships using a continuous, individual variability approach in children with a wide range of math abilities. In Study 2, we tested for differences in activation between children with and without MD to assess whether those with impaired math skills show dorsal stream anomalies. In both Studies 1 and 2, we gauged the relative strength of evidence for the null hypothesis versus the alternative hypothesis by generating Bayesian statistics in addition to frequentist statistics. If dorsal stream function underlying visual motion perception is indeed associated with math ability, we expected to observe a relationship between V5/MT activity and math performance in Study 1, and relative underactivation of V5/MT in the group with MD in Study 2.

2. Methods

2.1. Participants.

All participants were healthy, native English-speaking children and adolescents recruited from the Washington, DC metro area as part of a program of research on children with and without learning disabilities. None had a history of brain injury or neurological disorders. All participants received prizes and gift cards for their participation. All procedures were approved by Georgetown University's Institutional Review Board. Parents gave signed consent and their children signed assent.

2.1.1. Neuropsychological and demographic measures.

Intelligence was measured using the Wechsler Abbreviated Scale of Intelligence (Wechsler, 1991). Math performance was evaluated with the Calculation subtest (increasingly difficult untimed math problems) and Math Fluency subtest (timed arithmetic problems of single-digit addition, subtraction, and multiplication) on the Woodcock-Johnson Tests of Achievement III (Woodcock et al., 2001).

Given the high comorbidity of reading disability (dyslexia) and the math disability dyscalculia (Moll et al., 2018; Willcutt et al., 2013; Wilson et al., 2015), and the association between reading ability and visual motion perception (Cornelissen et al., 1995; Talcott et al., 1998), reading ability was entered as a covariate of no interest in the analyses. Single word reading was assessed using the Word Attack subtest (untimed pseudoword reading) of the Woodcock-Johnson Tests of Achievement III, and entered as a covariate of no interest in Studies 1 and 2. Similarly, due to the high comorbidity of Attention Deficit/Hyperactivity Disorder (ADHD) with learning disabilities (DuPaul et al., 2013), and to address potential confounds of inattention or impulsive/hyperactive behavior during the performance of the task in the scanner, ADHD symptoms were assessed using the Conners' Parent Rating Scale (either the Revised Edition or the 3rd Edition Short Form; Conners et al., 1998; Conners et al., 2008). The Inattention subscale was used as a covariate of no interest in the analyses for both studies since it was significantly elevated in the group with MD in Study 2.

Lastly, because prior studies have reported age-dependent differences in V5/MT activity (Klaver et al., 2008; Taylor et al., 2018), age was included as a covariate of no interest in the regression model used in Study 1, while for Study 2, we ensured the two groups were matched on age.

2.1.2. Study 1: Regression analyses to test for brain-behavior relationships.

Participants were 66 children and adolescents (31 male, 35 female) aged between 6 and 16 years with a wide range of math abilities, including those in the normal or above-normal range and those below the normal range. All participants had at least normal intelligence (Full-Scale IQ $\geq$ 85). Participant information is provided in Table 1. For 9 of the 66 participants, the Conners' Parent Rating Scale for ADHD symptoms was not available, leaving 57 participants in the summary statistics for Inattention and Impulsivity-Hyperactivity scores. Due to the wide range in chronological age, reading ability, and ADHD symptoms, and the potential relationships between each of these with brain activity during visual motion perception (described above), we controlled for these variables in the regression analyses (as described below).

	Group Mean (SD)	**Range8**
N	66	--
Age	10.1 (2.0)	6.3 - 16.1
Sex: M / F	31 / 35	--
Full Scale IQ	111.9 (13.2)	87 - 149
Calculation	101.3 (16.0)	61 - 132
Math Fluency	86.5 (17.2)	63 - 134

Word Attack	100.8 (15.5)	65 - 135
Inattention	60.2 (14.0)	42 - 90
Impulsivity / Hyperactivity	56.6 (11.8)	41 - 87

Table 1. Participant information for Study 1 (n=66). Group means (standard deviations) and ranges are shown for all measures. Full Scale IQ, math ability (Calculation and Math Fluency), reading ability (Word Attack) and measures of ADHD (Inattention and Impulsivity/Hyperactivity) represent standardized scores.

2.1.3. Study 2: Between-group comparisons of children with and without MD.

Participants in Study 2 were a subset of children from Study 1 who met the inclusion criteria for the Control group (n=18) or the MD group (n=23). Children in the Control group had to score ≥ 85 on both math subtests (Calculation or Math Fluency) and on the reading subtest (Word Attack). Children in the MD group, however, had to score <85 on at least one of the two math subtests, while having a score ≥85 on the reading subtest.

Participant information is provided in Table 2. As expected, based on these criteria, the Control group (11 male, 7 female) had significantly higher math scores than the MD group (7 male, 16 female) for both Calculation and Math Fluency (p<.0001). However, the groups also differed on sex distribution ($\chi^2(1)=3.9$, p=.0495), Full Scale IQ (t(39)=3.61, p=.0009), reading ability (Word Attack: t(39)=6.03, p<.0001), and ADHD symptoms (Inattention subscale of the Conners': (t(39)=-3.07, p=.0039). Due to these group differences, we included sex, IQ, Word Attack, and Inattention scores as covariates of no interest in the fMRI between-group comparisons (described below).

	Control	**MD**	**Group Comparisons**
N	18	23	
Age	10.0 (2.7)	10.6 (1.5)	.4149
Sex: M / F * (% M)	11 / 7 (61.1%)	7 / 16 (30.4%)	.0495^{+}
Full Scale IQ**	120.7 (12.9)	107.4 (10.6)	.0009

Calculation* **	115.2 (7.5)	97.0 (13.0)	<.0001
Math Fluency* **	107.7 (11.5)	76.0 (6.6)	<.0001
Word Attack* **	115.6 (12.8)	96.6 (7.2)	<.0001
Inattention **	53.3 (11.9)	66.3 (14.6)	.0039
Impulsivity / Hyperactivity	53.7 (9.1)	57.4 (13.0)	.3080

Table 2. Participant information for Study 2 (n=41). Group means (standard deviations) are shown. Two-tailed t-tests were used to test for differences in the means of the two groups on the continuous standardized measures while a chi^2 test was used to test for differences in sex distribution between the two groups ($^+$).

2.2. Task design specifications & participant preparation.

The task and fMRI acquisition procedures were the same for both studies and consistent with prior publications (Olulade et al., 2013; Taylor et al., 2018). We used a block design which included two active task conditions, Motion and Static, presented in alternating blocks (42s each), interspersed with blocks of a passive baseline, Fixation (21s). There were two blocks of Motion, two blocks of Static, and four blocks of Fixation per run. Further Fixation intervals (not included in analyses) were included at the beginning (9s) and end (6s) of each run to address magnetization effects. Each run (4m27s total) resulted in 28 whole-brain acquisitions for each of the three conditions, Motion, Static, and Fixation. About half of the participants had a second run which was included for the results presented here. An additional analysis was conducted where the number of runs was equated across the two groups, which yielded the same main findings.

For the Motion task, participants viewed low-contrast, random dot kinematograms consisting of gray dots (300 total) on a black background. While most dots moved randomly, with their direction changing constantly, a subset of dots (120 dots, 40%) moved coherently in either the left or right horizontal direction (randomly determined) at a constant speed of 3 deg/sec. Participants were asked to indicate the direction of the perceived coherent motion via button press with their left or right thumb, while maintaining fixation on a central cross. For the Static task, white dots were presented on a black screen, with density differing between left and right visual fields (density contrasts ranged between 35% and 65%; greater density side was randomly determined). Participants were asked to indicate which side had more dots via button press with their left or right thumb, while maintaining fixation on a central cross. The Static task was used to control for basic (non-motion) visual processing, motor action, eye movements, attention, etc. All analyses described here were carried out using the Motion>Static contrast (however, the main findings did not change when using the Motion>Fixation contrast instead).

For the active task conditions, Motion and Static, each 42s block consisted of 10 trials, and each trial included the stimulus (3s) followed by a fixation (1.2s). Seven participants in Study 1 and one in Study 2 were administered a slightly different version of this protocol, using three 30s blocks per active condition (rather than two 42s blocks), with each block containing 15 shorter trials (1.6ms stimulus followed by 0.4s fixation). These blocks were separated by 15s blocks of Fixation (instead of 21s), and the overall run (4m45s total) resulted in 30 whole-brain acquisitions for each condition (instead of 28). These minor protocol differences were considered to be inconsequential.

Tasks were presented to participants in the scanner using Presentation software (Neurobehavioral Systems, Inc., www.neurobs.com), which recorded accuracy and response times. Before entering the scanner, participants were trained on the tasks to become familiar with them and to avoid task learning in the scanner.

2.3. In-scanner performance.

The task was designed so that all participants would be able to perform well while eliciting task-specific activation. In-scanner behavior was assessed to ensure that participants were engaged throughout the run. We computed mean accuracy and response times (RTs) for all groups for the Motion and Static conditions, as well as for [Motion minus Static], consistent with the contrast used in the fMRI data analysis. While we did not anticipate between-group differences in Study 2, the means were compared between the group with and without MD using two-tailed independent samples t-tests. Two participants (in the Control group of Study 2) had no in-scanner behavioral data due to a technical error and thus were not included in these analyses of in-scanner performance.

2.4. Data acquisition.

Scans were acquired in the Center for Functional and Molecular Imaging at Georgetown University Medical Center on a 3.0T Siemens Trio Scanner. Functional images were acquired using a T2*-weighted gradient echo planar imaging sequence, using the parameters: TE=30ms; TR=3000ms; FA=90deg; FOV=192mm (in-plane resolution = 64 x 64; voxel size = 3mm x 3mm x 3mm), covering the whole brain; number of slices=50; slice thickness=2.8mm, 0.2mm gap; slice acquisition = sequentially descending axial slices.

2.5. Preprocessing.

All preprocessing, first level, and second level analyses were carried out in SPM12 run in MATLAB R2019b (The MathWorks Inc.) using batch scripting. Preprocessing steps included (in order): slice timing correction, motion correction realignment, coregistration with each participant's anatomical scan, segmentation, spatial normalization to MNI space, and smoothing.

Scans were corrected for head movement by estimating 6 linear rigid body parameters (x/y/z translation and pitch/roll/yaw rotation) and registering the images to the first volume. Volumes exceeding a 1.5mm threshold for scan-to-scan movement, or a 5% global signal change, were excluded from analysis. If any one run had greater than 20% of volumes excluded, then the whole run was discarded; if that participant had another run that was acceptable, it was kept in the analysis. A total of four participants were removed, resulting in the final group sizes reported in Tables 1 and 2. The 6 movement parameters were used subsequently as regressors of no interest. Smoothing was carried out using an isotropic Gaussian kernel with FWHM of 8mm.

A representative boxcar design was used to specify the onsets and durations of each block type and convolved with the canonical hemodynamic response function in SPM12. The data were modeled with a general linear model using additional regressors for the first temporal derivative of the block design, the six movement parameters to account for translational and rotational motion artifacts, and the global signal. The functional data were high-pass filtered at 128s to account for signal drift and corrected for autocorrelations using an AR(1) model.

2.6. Analysis.

2.6.1. Whole-brain analysis.

First, we performed a whole-brain analysis with all 66 participants for Motion>Static. The second-level statistical map was thresholded voxel-wise at $p<.001$ uncorrected, and cluster-wise at $p<.05$, corrected for family-wise error rate (FWE). Results are reported using MNI coordinates and corresponding Brodmann Areas, which were obtained using the BioImage Suite MNI2TAL tool version 1.2.0 (https://bioimagesuiteweb.github.io/webapp/mni2tal.html).

The peaks of activity from this whole-brain map were then used to generate ROIs for left and right area V5/MT by growing 5mm-radius spheres centered on the activation maxima (Fig. 1). These placements were used for all ROI analyses (Study 1 and Study 2) reported below. Extraction of the mean beta parameter values from these ROIs for the Motion>Static contrast was performed using MarsBaR v0.44 (Brett et al., 2002; http://marsbar.sourceforge.net/).

2.6.2. Study 1: Regression analyses to test for brain-behavior relationships.

Four regression models were conducted in the sample of 66 participants. Each model included the values extracted from one of the two V5/MT ROIs (left or right) and the scores from one of the two math performance measures (Calculation or Math Fluency). As noted above, age (years), reading ability (Word Attack), and ADHD symptoms (Inattention) were entered as covariates of no interest (scores for the latter were not available for 9 participants, so this analysis was carried out separately in four additional models with 57 participants). Frequentist statistics for the linear regressions were carried out in Stata version 16.1 (StataCorp, 2019).

We supplemented these frequentist linear regressions with Bayesian regressions performed on the same data derived from the left and right ROIs. While frequentist analyses can only provide evidence against the null hypothesis, not in favor of it, Bayes Factors quantify the relative amount of evidence for one hypothesis over another (Dienes, 2011; Wetzels et al., 2011). We followed the same process of entering each V5/MT ROI (left or right) and each math variable (Calculation or Math Fluency) in its own model, and using age (years), reading ability (Word Attack), and ADHD symptoms (Inattention, again in an additional analysis of 57 participants) as covariates of no interest. We report the statistic BF_{01}, which quantifies the odds ratio for the null model over the alternative model (Goss-Sampson, 2020; Wagenmakers et al., 2018). For these analyses, the “null” model included only the covariates of no interest (age, reading, and ADHD symptoms), so as to assess the support for including the math measure over and above the inclusion of these covariates; a $BF_{01}>1$ indicates relatively more evidence for the model that excluded the math factor. Bayesian analyses were conducted in JASP (JASP Team, 2020).

2.6.3. Study 2: Between-group comparisons of children with and without MD.

For between-group whole-brain comparisons, single-subject statistical maps for Motion>Static were submitted to independent samples t-tests (Control>MD and MD>Control) at the second level (thresholded voxel-wise at $p<.005$ uncorrected, and cluster-wise at $p<.05$, FWE-corrected).

Given the specific focus on area V5/MT, we followed the whole-brain analysis with an ROI analysis using mean activation values extracted from left and right V5/MT ROIs (placed in the same location as in Study 1). The mean activation values of the two groups were compared with independent samples t-tests using an alpha of .05.

Both the whole-brain and V5/MT ROI-based analyses controlled for sex, IQ, reading ability (Word Attack), and ADHD symptoms (Inattention), since these variables differed between the two groups.

These frequentist analyses were then followed up with Bayesian group comparisons, using the same extracted values from the left and right V5/MT ROIs. We again report the statistic $BF_{01,}$ which indicates the odds ratio for the null over the alternative hypothesis. An ANCOVA framework was used to determine whether there was evidence in favor of including group as a factor, or in favor of the null hypothesis (exclusion of group as a factor), while again controlling for the covariates of no interest that differed between the groups (sex, IQ, reading ability, and ADHD symptoms). Bayesian analyses were conducted in JASP (JASP Team, 2020).

2.7. Preregistration.

The background, predictions, and methods for this study were preregistered on the Open Science Framework (https://osf.io/693tm) prior to any analysis of the data. Details of the changes to the original preregistration can be found in the Transparent Changes Document under the same OSF project. The major changes were: (1) conduct group comparisons between a group with MD and a Control group, with sex, IQ, reading ability and ADHD symptom scores as variables of no interest; (2) to add Bayesian statistics, for the purpose of weighing the relative strength of the non-significant findings; and (3) to curtail further analyses (e.g., not to include functional connectivity analyses).

3. Results

3.1. Study 1: Regression analyses to test for brain-behavior relationships.

3.1.1. In-scanner performance.

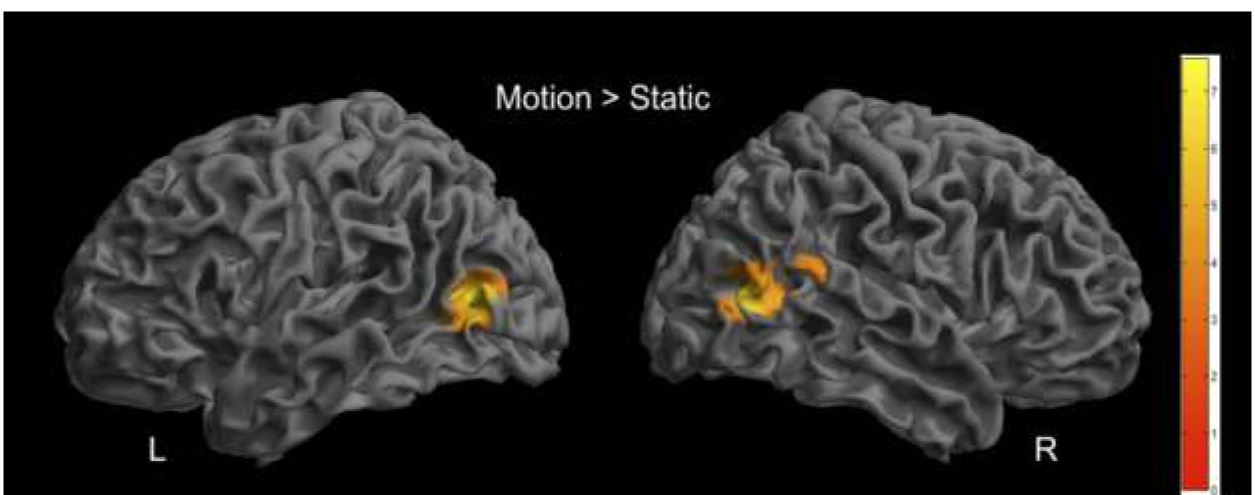
As expected, the group of 66 children/adolescents performed the Motion and Static tasks with ease, obtaining high accuracy (greater than 90% on average) and with the expected response times (Table 3).

	Accuracy (%)	RT (ms)
Motion	91.4 (13.1)	1378.0 (337.5)
Static	96.3 (7.1)	1126.5 (262.4)
Motion - Static	-4.8 (11.4)	251.5 (313.0)

Table 3. In-scanner performance for Study 1. Group means (standard deviations) for accuracy and response times for each task, as well as for the difference between them ([Motion minus Static], the contrast used to generate activation maps).

3.1.2. Whole-brain activation.

The whole-brain activation statistical map for Motion>Static in all children/adolescents revealed activity in left and right area V5/MT as depicted in Fig 1.



Region	Brodmann Area	x	y	z	Number of Voxels	Z-score
Left lateral occipital lobe (V5/MT)	BA 19	-45	-73	5	197	6.69
Right lateral occipital lobe (V5/MT)	BA 19	48	-70	8	306	6.11

Figure 1. Whole-brain activation results for Study 1. Activation during visual motion processing (Motion>Static) was located in left and right area V5/MT for the group of 66 children/adolescents.

3.1.3. Frequentist regressions.

Next, the mean signal extracted from ROIs centered on the two peak coordinates reported above was used to test for relationships between mean activation during visual motion perception (in left or right V5/MT) and mathematical performance (for Calculation or Math Fluency), while controlling for age and reading ability (or for age, reading ability and ADHD symptoms). All regression coefficients for brain activity and math scores were found to be non-significant (Table 4).

3.1.4. Bayesian regressions.

Bayesian regression analyses (performed on the same data used in the frequentist regression above) indicated that the data did not support the existence of a relationship between activation in left or right V5/MT ROI and either math measure (Calculation or Math Fluency). That is, in all cases, there was more evidence for the null models that excluded the math factor (and only contained covariates of no interest) compared to the models that included the math factor (plus covariates of no interest), with all $BF_{01}>1$. Specifically, when controlling for age and reading, the range of BF_{01} values indicated approximately 2.4 to 2.9 times more support for the null models (1.6 to 2.3 times more support when adding inattention scores as a nuisance predictor in 57 of the participants; Table 4). Each of these BF_{01} values individually indicate anecdotal evidence for the math measures' exclusion (Wetzels et al., 2011; Jeffreys, 1961); when taken together, they support the absence of a relationship between V5/MT activity and math skills. In no case was the model that included all covariates and the math factor (the "full" model) the model that was most supported by the data (the "best" model). When comparing the full models to the best models, BF_{01} values indicated there was approximately 6.0 to 9.6 times more evidence for the best model than the full model; these values indicate overall evidence against the inclusion of the math factors.

		Regressions Including Age and Reading (n=66)		Regressions Including Age, Reading, and ADHD (n=57)	
ROI	**Math Factor**	**P-value**	**BF_{01}**	**P-value**	**BF_{01}**
Left V5/MT	Calculation	0.74	2.77	0.79	2.25
Right V5/MT	Calculation	0.72	2.44	0.91	2.15
Left V5/MT	Math Fluency	0.96	2.90	0.63	2.11
Right V5/MT	Math Fluency	0.90	2.55	0.39	1.62

Table 4. Frequentist and Bayesian regression results. Frequentist p-values correspond to the coefficient of the math factor included in the model, while BF_{01} values correspond to the support for the null model (including only covariates of no interest) over the alternative, "full" model (including covariates and the math factor of interest). Together these complementary analyses demonstrate that there is no relationship between mean activation during visual motion perception (in left or right V5/MT) and mathematical performance (for Calculation or Math Fluency).

3.2. Study 2: Between-group comparisons of children with and without MD.

3.2.1. In-scanner performance.

As anticipated, there were no differences in accuracy between the Control group and the group with MD for the Motion task or the Static task. There were also no between-group differences in response times for the Motion task, but the group with MD had relatively longer RTs for the Static task (t(37)=-2.34, p=.02). Importantly, given the interest of Motion>Static for the activation map, there were no between-group differences in accuracy or response times for the comparison of [Motion minus Static] (t(37)=0.62, p=.54 for accuracy; and t(37)=0.88, p=.38 for RTs; Table 5).

	Accuracy (%)			RT (ms)		
	Control	**MD**	**Group comparison**	**Control**	**MD**	**Group comparison**
Motion	97.2 (5.5)	92.3 (13.3)	p=.18	1343.5 (337.5)	1438.9 (322.6)	p=.38
Static	98.3 (2.4)	95.6 (10.1)	p=.31	1039.8 (193.9)	1227.4 (276.2)	p=.02
Motion - Static	-1.1 (6.5)	-3.3 (12.9)	p=.54	303.8 (265.0)	211.5 (355.3)	p=.38

Table 5. In-scanner performance for Study 2. Group means (standard deviations) for accuracy and response times (RT) for each task, as well as the difference [Motion minus Static], the contrast used to generate the activation maps. Two-tailed t-tests were used to test for

differences between the two groups.

3.2.2. Frequentist whole-brain activation.

Activity in left and right area V5/MT emerged from the whole-brain activation statistical maps of Motion>Static for the Control group (MNI coordinates: -42, -73, +11, and +57, -64, +14) and likewise, for the group with MD (MNI coordinates: -45, -73, +5, and +39, -64, +8). However, when comparing the Controls with the group with MD at the level of the whole brain (controlling for sex, IQ, reading ability, and ADHD symptoms), there were no differences between the two groups (either Control>MD or MD>Control).

3.2.3. Frequentist ROI analysis.

Mean values extracted from the left and right V5/MT ROIs (same ROIs/locations as in Study 1) were compared between the two groups while controlling for the covariates of no interest (sex, IQ, reading ability, and ADHD symptoms). These analyses also showed no differences between the Control group and the group with MD.

3.2.4. Bayesian ROI analysis.

Using the same left and right V5/MT ROI data as used in the frequentist analysis above, Bayes Factor analyses indicated that the data did not support the inclusion of group as a factor in the models. Specifically, when controlling for sex, IQ, reading ability, and ADHD symptoms, the BF_{01} values indicated that in the left hemisphere, there was approximately 1.9 times more evidence for the null model that excluded the group factor (and only contained the covariates of no interest), and in the right hemisphere, there was approximately 2.4 times more evidence for the null model (with only the covariates), in comparison to the model that included the group factor (plus covariates of no interest). These values indicate anecdotal evidence in favor of excluding the group factor from the model (Wetzels et al., 2011; Jeffreys, 1961). However, when comparing the model that included all covariates and the group factor (the “full” model) to the model most supported by the data (the “best” model; in this case, the true null model containing only a constant), BF_{01} values indicated there was 23.5 times more evidence in the left hemisphere and 55.9 times more evidence in the right hemisphere for the best (null) model than the full model. These values indicate overall evidence against the hypothesis that activity differs by group.

4. Discussion

This study is the first to our knowledge to use functional neuroimaging to answer the question of whether activation underlying visual motion processing in area V5/MT relates to math ability, and whether this dorsal visual stream function is compromised in the math disability dyscalculia, as has been suggested in prior behavioral studies (Boets et al., 2011; Braddick et al., 2016; Sigmundsson et al., 2010). Based on prior studies, one might have expected to see (i) a relationship between area V5/MT activity and math ability; and (ii) relative underactivation of V5/MT in the group with MD compared to the Control group. However, our assessments of continuous brain-behavior relationships across a sample with a wide range of math skills indicated no relationships between V5/MT activity and math ability. Furthermore, our between-group comparison of brain activation during visual motion processing revealed no differences between children with and without MD. In addition to classical frequentist statistics, we employed Bayesian statistics, which are helpful for interpreting null findings. Both the Bayesian regressions and between-group comparisons indicated more evidence for the null hypotheses, i.e. that there were no relationships between activity underlying visual motion processing and math performance measures, and no differences in brain activity between our two groups, compared to the alternative hypotheses. Thus, we conclude that in children/adolescents, there is no relationship between brain activity in area V5/MT during visual motion perception and math ability, and that those with the math disability dyscalculia do not show aberrations in area V5/MT during visual motion processing.

Our study was motivated by the hypothesis that coherent motion processing is related to math ability, due to their reliance on dorsal stream structures with a shared developmental trajectory. This hypothesis is supported by the finding of a link between coherent motion sensitivity in kindergarten and arithmetic ability in third grade (Boets et al., 2011); as well as a report of a concurrent relationship between visual motion sensitivity and mathematical skills (Braddick et al., 2016). Further, Sigmundsson and colleagues (2010) reported less sensitivity to coherent visual motion in a group of children with math disability compared to controls. All of these studies used behavioral measures of visual motion processing, and made inferences about the involvement of underlying neural systems, which we tested directly in the present study. Our findings of an absence of a relationship between area V5/MT activity and math ability, as well no differences in activity in V5/MT between the groups with and without MD, compels us to consider whether our null findings may have been due to anything specific about our experimental approach. We consider these approaches as well as those used in prior studies, to shed light on the question of a relationship between visual motion processing and mathematical ability.

First, we consider the tasks used. Coherent motion detection is commonly employed to study the dorsal visual pathway and for eliciting functional activation (Braddick et al., 2001; Britten et al., 1992; McKeefry et al., 1997; Rees et al., 2000; Watson et al., 1993; Wattam-Bell, 1994). This approach used in imaging studies differs from adaptive staircase procedures used in the aforementioned behavioral studies of visual motion perception. Specifically, behavioral studies with adaptive designs attempt to identify the thresholds (minimum percentage of dots moving coherently) where participants can still accurately perceive the direction of coherent motion. Such a design is not very suitable for fMRI studies (e.g., due to it resulting in a different number of trials per participant). The approach used for neuroimaging studies involves the contrast of two active conditions, Motion and Static, with the main goal of optimally driving neurons in V5/MT that are selective for moving objects and hence result in changes in fMRI signal. Coherence of the moving dots was fixed at a level meant to be perceptible to all participants, so that they could perform with high accuracy. The fact that the MD and Control groups did not significantly differ in performance on the [Motion - Static] comparison indicates that both groups were successfully engaged in the tasks (see Table 5). This design has the advantage of deliberately avoiding between-group performance differences, so as not to confound the interpretation of the fMRI results (Price et al., 2006). The specific task used here has been used previously in our lab to study area V5/MT activity in children/adolescents and to identify differences between groups (Olulade et al., 2013; Taylor et al., 2018), and the task is similar to that used in other studies examining brain function during coherent motion perception (Braddick et al., 2001; Helfrich et al., 2013; McKeefry et al., 1997; Tootell et al., 1995; Watson et al., 1993; Zeki et al., 1991). Thus, while our task is not directly comparable to behavioral studies, it is consistent with the published imaging literature on visual motion perception and is a fitting choice to tap into dorsal stream processing and reveal differences, should they exist.

We next consider our choice of ROIs. Our task successfully elicited activity in our participants in bilateral area V5/MT, situated in dorsal occipitotemporal cortex. V5/MT is considered to be the main cortical site for visual motion processing as part of the magnocellular-dominated dorsal pathway of the visual system (McKeefry et al., 1997; Sunaert et al., 1999; Tootell et al., 1995; Watson et al., 1993), which is why it was the region targeted for this investigation. For the main analyses in Study1 and Study 2, we used ROIs derived from spheres centered on the locations of the maxima of left and right V5/MT borne out of the whole brain analysis in Study 1 (66 participants). The locations of these maxima are highly consistent with coordinates reported in prior studies of children/adolescents (Klaver et al., 2008; Taylor et al., 2018) and adults (Dupont et al., 1994; McKeefry et al., 1997; Sunaert et al., 1999; Watson et al., 1993; Zeki et al., 1991). However, in light of our results and to test *post hoc* if the null findings were attributable to the placement of these ROIs, we repeated the analyses using spheres centered on the left and right V5/MT maxima reported for an independent group of children (MNI coordinates: -50, -74, +8 and +51, -69, +7; Taylor et al., 2018); we found that this approach did not alter any of the main results. Further, to address any concerns that this particular ROI approach using mean activation across the ROIs may bias toward a negative finding, we also performed a voxel-wise analysis (with small volume correction) within the clusters from the Study 1 group map. Using the clusters as inclusive masks, we performed regressions (as in Study 1) and group comparisons (as in Study 2) within each voxel. For this analysis we again found no brain-behavior relationships and no group differences. Taken together, the activity we identified in left and right area 5V/MT for the entire group was highly consistent with the location reported in the literature, yet there were no results in support of a relationships between this activity and math performance.

Turning to the assessments of math ability, our measures were age-normed psychoeducational tests, widely used in the United States for studies of mathematical cognition and math disability. The Calculation subtest of the Woodcock-Johnson III is an untimed paper-and-pencil test with mathematical problems that increase in difficulty, ranging from number writing, to single- and double-digit calculation, to geometry and trigonometry. The Math Fluency subtest, also from the Woodcock-Johnson III, is a timed test of single-digit addition, subtraction, and multiplication problems. It is likely that the Calculation subtest relies more on procedural computation and visuospatial strategies, which are attributed to bilateral dorsal cortical function, while the Math Fluency subtest involves arithmetic of small numbers, which tends to rely on retrieval-based strategies in left hemisphere language regions (Campbell & Xue, 2001; Prado et al., 2014; Tschentscher & Hauk, 2014; Zamarian et al., 2009). A relationship between the activity during visual motion processing and the Calculation subtest was therefore expected to be relatively more likely. Indeed, the study by Braddick and colleagues (2016) showed a correlation between global motion coherence thresholds and the same Calculation subtest; they also showed a correlation with the Woodcock-Johnson Applied Problems subtest. However, they did not find a relationship between dorsal stream brain structure and math performance on either of these measures. Turning to the other studies, math ability was measured in several different ways. Boets and colleagues (2011) measured the response times and accuracy of subtraction on a computer (third-graders verbally responded to the problem and the investigator pressed a button to record response times). They found that speed, but not accuracy, of subtraction was correlated with coherent motion sensitivity. These analyses, however, did not control for age, which could be correlated with both coherent motion perception and math skill. Lastly, the behavioral study by Sigmundsson and colleagues (2010), which found poorer visual motion perception in children with MD compared to controls, used a math achievement test linked to the children's curriculum. Specifically, it was used to identify the worst and highest performing 10% of a group of 73 children, and compared these (6 participants per group) to each other. Taken together, multiple math measures have been used previously to assess relationships between visual motion processing and math ability. We used two math measures which covered a wide range of abilities, including untimed and timed problem-solving, and complex mathematics as well as simple single-digit arithmetic. Our math measures were therefore appropriately equipped to establish evidence for a connection between dorsal stream function during visual motion processing and calculation-based arithmetic, if it were to exist.

In terms of study design, we used a two-pronged approach to align with prior studies. First, we performed linear regressions, allowing us to assess brain-behavior relationships from a continuous, dimensional perspective, as has been recommended in literature on learning disabilities (Branum-Martin et al., 2013; Peters & Ansari, 2019). We found no relationships between V5/MT activation and mathematical performance. Then, for consistency with a prior behavioral study comparing children with strong versus low math ability (Sigmundsson et al., 2010), we compared activation between children with and without MD and found no differences. In addition, we employed Bayesian statistics in both approaches to determine the relative amounts of evidence for the alternative hypothesis versus the null hypothesis. We found that Bayes Factors in both studies indicated consistent evidence in favor of the null hypotheses over the alternative hypotheses. In both studies, we also controlled for reading ability and symptoms of ADHD on a continuous scale, as there is high comorbidity between reading disability and math disability (Willcutt et al., 2013; Wilson et al., 2015), as well as between ADHD and math/reading disabilities (DuPaul et al., 2013). Inclusion of these covariates is an advantage over previous studies which did not control for these factors.

The prevailing theory in the literature is that the difficulties in arithmetic fact encoding and retrieval in MD are due to impaired number sense, with other cognitive deficits likely contributing as well (Butterworth, 2010; Fias et al., 2013; Geary & Brown, 1991; Geary & Hoard, 2001; Piazza et al., 2010; Wilson et al., 2015). This hypothesis has been supported by brain imaging studies showing abnormal brain function during arithmetic and magnitude judgment tasks in those with MD in bilateral frontoparietal regions (Ashkenazi et al., 2013a; Peters & De Smedt, 2018) such as the intraparietal sulcus (IPS) (Price et al., 2007). The IPS is known to receive direct projections from V5/MT in non-human primates (Baizer et al., 1991; Maunsell & Van Essen, 1983) and is responsive to coherent visual motion in humans and non-human primates (Braddick et al., 2001; Colby et al., 1993; Orban et al., 2006; Sunaert et al., 1999), with specific subsegments of the IPS showing responses lower than those in V5/MT (Helfrich et al., 2013). In the present study, we did not observe activation in the IPS, nor did differences in IPS activation emerge from the between-group comparison. While the IPS was not the focus of this investigation, the question arises whether placement of an ROI here (as we did for area V5/MT) would reveal relationships between activation during visual motion perception and mathematical performance, or group differences in activation. We addressed this *post hoc* with ROIs centered on the left and right IPS using coordinates reported in the literature (MNI coordinates: -22, -49, +57 and +34, -51, +59; Braddick et al., 2001). We found no relationships between mean activity within the IPS ROIs and math skills in the sample of 66 children, nor did we find any differences in mean IPS activity in the ROIs when comparing the groups with and without MD. These results suggest that while portions of the IPS are involved in visual motion perception, and some may even be responsible for both visual motion processing and the representation of numbers (Renzi et al., 2011; Salillas et al., 2009; Schwiedrzik et al., 2016), any neuronal activity induced here by our coherent motion perception task is minimal and not related to mathematical ability. Area V5/MT is widely accepted as the hub of coherent visual motion processing and has been frequently studied in humans (e.g., Hampson et al., 2004; McKeefry et al., 1997; Tootell et al., 1995; Watson et al., 1993) and non-human primates (e.g., Albright, 1984; Dubner & Zeki, 1971; Maunsell & Van Essen, 1983; Ungerleider et al., 1984; see Zeki, 2015 for review). Our results indicate that area V5/MT is spared disruption in MD, and, given the bottom-up nature of the dorsal stream, one would therefore not expect anomalies in the IPS during visual motion processing, either. In this context, one interpretation of the dorsal vulnerability model would be that dysfunctional development of the dorsal stream would broadly impair all functions which rely on these structures. However, in the current study, our focus was limited on the relationship between activity underlying visual motion perception and math performance. Future studies could investigate the relationship between activity underlying visual motion perception and other dorsal stream tasks (e.g. visuospatial cognition, attention, and visuomotor control).

Lastly, we consider potential limitations of our study. Beginning with the sample sizes, our group of children/adolescents with MD was necessarily limited as we only included participants who had an isolated math impairment (<85 on one of the Woodcock-Johnson measures of math), while having reading scores in the normal range (≥85 on the Woodcock-Johnson measures of reading). Yet 23 participants in the group with MD and 18 in the Control group were large enough to yield meaningful results: they are larger than prior fMRI studies comparing groups during visual motion processing (Brieber et al., 2010 with 15/15; Olulade et al., 2013 with 14/14; and Taylor et al., 2018 with 13/15 per group) and significantly higher than those used by Sigmundsson and colleagues (2010), who had six participants per group. These group sizes are also consistent with imaging studies comparing groups of MD and controls in the broader math disability literature (e.g. Jolles et al., 2016 with 19/19; and Rosenberg-Lee et al., 2015 with

16/20 per group; however see Bulthe et al., 2019 with 24/24 per group;). Our sample size of 66 in Study 1 affords further power and variability to detect brain-behavior relationships, should they exist. As noted above, although the task design was consistent with other fMRI studies investigating coherent motion processing and is in line with best practices (Price et al., 2006), it necessarily limits our ability to investigate behavioral performance differences between the two groups. Future studies could conduct both a behavioral assessment of visual motion thresholds using an adaptive staircase procedure and an fMRI investigation using predetermined coherence levels. Having both sets of data in the same participants would better bridge the behavioral with the neuroimaging literature. Lastly, and as noted above, given that the dorsal stream vulnerability hypothesis also suggests a relationship between coherent visual motion perception and other dorsal stream tasks, future studies should extend the number of measures assessed, including visuospatial functions.

Taken together, our findings do not support a dorsal stream deficit where poor math performance is accompanied by poor visual motion processing. Thus, this study conflicts with previous claims that math disability fits into a framework of dorsal stream vulnerability (Braddick et al., 2016). Braddick and colleagues (2016) argue that global motion processing is a sensitive indicator of children's typical and atypical brain development, especially in areas of calculation, numerical skills, and visuomotor integration, due to their shared underlying substrates in the dorsal visual stream. However, our results suggest that it would not be advisable to use this task as a marker of cognitive or neural development in children with math disability. Furthermore, our results indicate that math disability may not fit into the dorsal stream vulnerability framework, at least one that assumes all functions of the dorsal stream must be concurrently impaired. While other functions of the dorsal visual stream are impaired in MD, impaired processing does not appear to begin in earlier regions such as V5/MT. Thus, our study is a first step towards showing that dorsal stream dysfunction on a broader level is unrelated to math ability. Characterizing the nature of MD, including which aspects of the dorsal pathway are intact, has important implications for theoretical models of MD, its diagnosis, and ultimately its treatment. Our results are consistent with current treatment practices based on the cognitive models of number processing, which use pedagogic reinforcement of symbolic number representations used in procedural arithmetic, and appear to normalize IPS function (see Iuculano, 2016 for review).

In conclusion, we found no evidence of a relationship between activity underlying visual motion processing in area V5/MT of the dorsal visual pathway and mathematical ability. This conclusion is based on linear regressions in a sample of children/adolescents with a range of math abilities, as well as between-group comparison of children/adolescents with and without MD, with both approaches incorporating Bayesian analyses. Our results represent a further step into understanding the neurobiology and manifestation of the math disability developmental dyscalculia.

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