



# Cerebellar Activation During Reading Tasks: Exploring the Dichotomy Between Motor vs. Language Functions in Adults of Varying Reading Proficiency

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## Abstract

The nature and extent to which the cerebellum contributes to language processing is not clear. By using fMRI to examine differences in activation intensity in areas associated with motor and language processes, we advance our understanding of how this subcortical structure contributes to language and, more specifically, reading. Functional magnetic resonance imaging data was collected from two groups of adults. One group was classified as typical (proficient) readers, and the other as atypical (less proficient) readers. fMRI was used to measure cerebellar activation during silent reading and silent rapid naming tasks, which differed in degree of language and motor/articulatory processing. Regions of interest associated with motor and language processing were examined in order to compare how cerebellar activation in typical and atypical readers differed as a function of task both within and between groups. Significant differences in activation intensity were noted between individuals of typical and atypical reading proficiency in cerebellar regions associated with motor, but not language processing, during a silent word-reading condition. Additionally, readers who were less proficient showed no differences in activation between tasks in each of the regions of interest within the cerebellum. We provide evidence that, in typical readers, the cerebellum is functionally specialized for reading tasks that vary in language and articulatory processes. In accordance with prior research, we demonstrate that less-proficient adult readers show decreased functional specialization within the cerebellum during reading tasks. We also show that regions of the cerebellum associated with motor/articulatory processing are different between typical and atypically reading adults. Finally, to our knowledge, this is the first brain-imaging study to specifically examine cerebellar activation during rapid naming tasks and we discuss the implications for these findings with regard to current theoretical models that emphasize the link between reading and speech production.

**Keywords** Cerebellum · Dyslexia · Reading · fMRI · Speech production

Reading is a unique human ability that requires coordination of neural networks located throughout the brain [1]. Modern

brain-imaging methods including functional magnetic resonance imaging (fMRI) have provided new insight into how these networks are organized and structured. However, many outstanding questions remain, including the nature and extent of cerebellar contributions to reading.

Traditional accounts of cerebellar function conceptualize it as a “slave system” that wholly subserves motoric processing demands from the cerebral cortex (see [2], for review). However, there is converging evidence that the cerebellum also plays an important role in cognitive processes [2–7], including language and reading (for a recent review, see [5]; also [4, 6, 7]). How these motor + language processing functions should be characterized in the cerebellum remains unclear [3, 8–11]. In the case of reading, the nature of cerebellar involvement has become a matter of some controversy [12–15].

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Support for the cerebellum's purported influence on reading comes from evidence of substantive differences in cerebellar structure and function that have been identified in individuals with reading deficits [7, 9, 13, 16–18]. In addition, cerebellar characteristics have been linked to specific aspects of behavioral reading performance (e.g., [19]). However, some researchers have questioned how these findings in a “motor-based” structure are related to reading impairment, which is more commonly associated with difficulties in phonological processing [13, 20, 21].

It is apparent that understanding more about the nature of how the cerebellum contributes to reading is important to advance the field of reading research, and to help clarify the role of subcortical structures in language. This leads us to the present study, which examines differences in cerebellar activation in adults of typical (TR) and atypical (AR) reading proficiency. By utilizing an fMRI paradigm with tasks varying in language and motor/articulatory complexity, we aim to examine the nature of the motor and language functions of the cerebellum and their relationship to skilled and accurate reading.

## The Cerebellum and Reading

The cerebellum plays an important role in many aspects of the reading process, including articulation, verbal working memory, verbal fluency, and grammatical processing (see [22], for review), phonological assembly and semantic processing [23], and semantic categorization [24]. As such, the contribution of the cerebellum to reading varies as a function of task [23]. For example, one fMRI study showed that phonological assembly (i.e., rhyme judgment of visually-presented nonsense words) resulted in increased activation in bilateral posterior and inferior regions of the cerebellum relative to a control task (i.e., judging left/right orientation of visually presented lines; [23]). In the same study, participants' categorization of common nouns into semantic categories (e.g., determining if “man” and “boy” belonged to the same category) resulted in cerebellar activation in similar regions as the phonological assembly task, but also in the right cerebellar nuclei, inferior vermis, and right posterior regions, relative to the control condition, suggesting that cerebellar involvement in reading shifts according to the task at hand.

**The Cerebellar Deficit Theory of Reading Disorder** In recent decades, it has been suggested that subtle differences in cerebellar function may lead to generalized cognitive and behavioral differences in some individuals [25]. These differences may manifest as deficits in executive function, cognitive processing, working memory, verbal fluency, rapid automatized naming (RAN; which refers to the ability to quickly and accurately name familiar letters, numbers, colors, and objects) speed, and decreased reading proficiency [7, 15, 25–27]. Relevant to

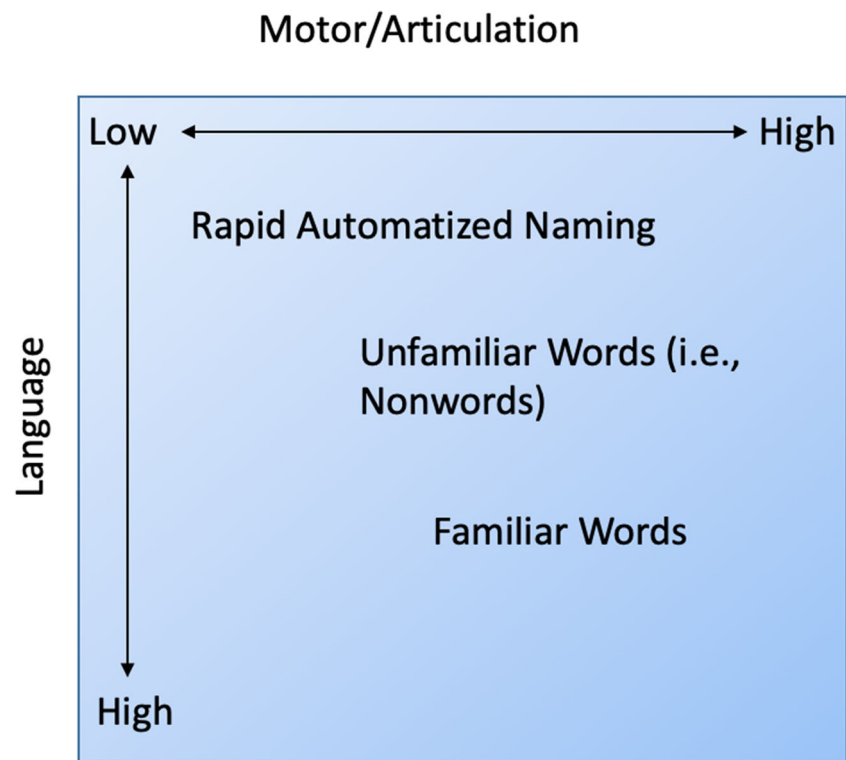
the current work, there is evidence that suggests many individuals with reading difficulties have measurable differences in cerebellar structure and function. The results of a recent meta-analysis indicated that people with reading difficulties had significant variability in gray matter volume in the right cerebellar hemisphere (and throughout the brain) when compared to typical readers [28]. Reduced gray matter volume in the right hemisphere of the cerebellum has also been described both in children [29] and adults [26] with reading difficulties.

Findings from recent fMRI studies suggest there are also functional differences in cerebellar patterns of activation for typical and atypical readers. Specifically, results of fMRI studies indicate that the blood oxygen level-dependent (BOLD) response (an indirect measure of neuronal activity) differs in readers with typical and atypical or poor reading abilities [12, 19]. Evidence suggests that this effect occurs across languages and orthographies [18, 30]. For example, [12] study of 22 children (15 of whom were classified as having a reading disorder (RD)) determined that children with typical reading ability displayed similar patterns of activation during a noun-verb association task, whereas those with RD tended to have diffuse, highly variable patterns of activity that were scattered throughout the cerebellum. Differences in cerebellar activation patterns have also been noted between typical and atypical readers in other reading tasks, including those that rely on the print/letter representations (i.e., orthographic) and sound representations (i.e., phonological processing; [30]).

Overall, we have evidence that the cerebellum plays a role in reading and language processing; however, to what extent this contribution is driven by motor and/or cognitive demands is not well understood. Further, it has not yet been established if there are observable differences in cerebellar activation in individuals with RD, particularly during tasks that vary in the motor (articulatory) component and cognitive demands (i.e., rapid naming, reading familiar words, reading unfamiliar words; see Fig. 1). Finally, if these differences do exist, it is unknown whether they will manifest in regions of the cerebellum associated with language and cognitive processing, those associated with motor control of articulatory processes, or both.

Reading and rapid naming tasks are an ideal way to examine the distinction between language and motor processing in the cerebellum because they both involve articulatory fluency but differ in automatic versus effortful processing demands that subserve speech production and reading. Notably, the regional networks associated with articulation are shown to be active during both overt (reading aloud) and covert (silent) reading tasks and for both familiar (i.e., real words, *hint*) and unfamiliar stimuli (i.e., nonwords, *bint*) [31]. As such, the potential confound of overt articulation differences between typical and atypical readers (i.e., slowed response times) can be removed by using a silent reading task. These tasks then afford us the ability to test the extent to which individuals with reading impairments show similar patterns of activation in regions of the cerebellum associated

**Fig. 1** Motor/articulatory and language demands of reading and rapid naming. This figure illustrates how automatic and cognitive processing demands vary as a function of reading task



with motor functions compared to those associated with language functions. This purpose of this study was to answer the following questions:

- *Question 1 (within subjects):* Do individuals who are atypical readers show decreased functional specialization for reading and rapid naming tasks in regions of the cerebellum associated with motor/articulatory and language processing?
- *Question 2 (between subjects):* Are there differences in brain activation between individuals of typical and atypical reading proficiency during reading tasks and rapid naming tasks that vary in degree of motor/articulatory processing?
- *Question 2A:* If these differences are present, do they manifest in cerebellar regions associated with motor/articulatory functions, language functions, or both?

## Methods

### Experiment

This experiment was conducted as part of a large-scale, multi-part fMRI investigation of reading and rapid naming in individuals with and without reading disorders. More information about the experimental design and protocols can be found in Cummine et al. [32].

### Participants

Data from 32 participants was analyzed (9 female, 29 right-handed, mean age =  $21.3 \pm 2.5$  years). Of these, 18 individuals (5 female, 17 right-handed, mean age =  $20.4 \pm 2.8$  years) were classified as typical readers (TR), as indicated by a score lower than .25 on the Adult Reading History Questionnaire (ARQ; [33]), a self-reported measure of reading performance, and a minimum standard score of 90 on the Test of Word Reading Efficiency, Second Edition (TOWRE-2), which measures sight word reading and phonemic decoding efficiency [34]. The remaining 14 individuals (4 female; 11 right-handed; mean age =  $22.3 \pm 2.3$  years) were classified as atypical readers (AR), as indicated by a score at or above .45 on the ARQ, and a standard score of at least one standard deviation below the skilled group on the TOWRE-2. All participants had normal or corrected-to-normal vision and spoke English as a primary first language. Consent was obtained according to the Declaration of Helsinki (2013, <http://www.wma.net/en/10home/index.html>) and the experiment was performed in compliance with the relevant laws and institutional guidelines and was approved by the host University Health Research Ethics Board. All participants were paid a small honorarium.

### Materials

**Reading Tasks** A  $6'' \times 8''$  grid was created, into which 100 real words were presented over five cards that each consisted of

$4 \times 5$  matrices of stimuli (i.e., 20 words presented in each matrix). Similarly, 100 nonwords were presented over five cards that consisted of  $4 \times 5$  matrices of stimuli (i.e., 20 nonwords presented in each matrix). The words/nonwords were presented in Calibri 68-pt. font. The nonwords were created by changing one or two letters of the real words while maintaining typical English orthographic patterns. Characteristics of the stimuli were extracted from the English Lexicon Project (<http://elexicon.wustl.edu/default.asp>; [35]) and are listed in Supplementary Table 1. Real words and nonwords were all monosyllabic, four letters long, and pronounceable.

**Rapid Naming Task** A standard  $4 \times 9$  matrix of letters (i.e., c, n, s, a, k, t) as per the Comprehensive Test of Phonological Processing–2 (CTOPP-2; [36]) was used. To closely match the size/dimensions of the word/nonword stimuli, a  $6'' \times 8''$  grid was created that was partitioned into 36 cells. The six letters were randomly inserted into the matrix with the following restrictions: (1) no letter was presented more than two times in a row, (2) no letter was presented twice in sequence (including controlling for a letter presented at the end of a row and the beginning of the next row). The letters were presented in Calibri 68-pt. font. Following this procedure, five unique matrices of letters were created.

**Baseline Task** Finally, to control for, and partial out the effects of eye movements, a  $4 \times 9$  matrix of fixation crosses was created that matched the size and dimensions of the letter matrix and was used as a baseline in the first-level modeling (described below).

## Procedure

Participants completed the behavioral reading assessments as described above, then arrived at the neuroimaging center where they were cleared for safe participation by the magnetic resonance (MR) technician. Participants were given instructions about the nature of the tasks they would be completing. Stimuli were presented using a data projector connected to the computer running E-Prime software (Psychology Software Tools, Inc., <http://www.pstnet.com>). For each task (real words, nonwords, letters), a block design was used that alternated task blocks with fixation blocks. Each matrix, whether stimulus or fixation, remained on the screen for 25 s. Within a particular reading (real words or nonwords) or rapid naming (letters) condition, five different matrices were presented in a random order so that participants did not receive the same matrix more than once. The order of presentation of the reading and rapid naming tasks was counterbalanced across participants. For all task and fixation matrices, participants were instructed to silently name the matrix of stimuli, starting at the top left and moving right through the rows, and press a button [37] when they reached the end of a matrix, and to then start again at the beginning of the matrix, for as many times as possible in the 25 s that the matrix was visible (see Fig. 2).

## Data Acquisition

Images were acquired on a 1.5T Siemens Sonata scanner and were positioned along the anterior-posterior-commissure line. Anatomical scans included a high-resolution axial T1 MPRAGE sequence with the following parameters: TR = 2000 ms, TE = 4.38 ms, number of slices = 112, base resolution  $256 \times 256$ , voxel size  $1 \times 1 \times 1$  mm, scan time 4:48 min. For each task (real words, nonwords, rapid naming of letters), 136 volumes of 36 slice, axial spin, echo planar images (EPIs) were obtained with the following parameters: TR = 1970 ms, TE = 40 ms, base resolution  $64 \times 64$  with a  $128 \times 128$  reconstruction matrix that improved pixel resolution through zero-filling prior to Fourier transform reconstruction, scan time 4:41 min per task. EPI slice thickness was 4 mm with no gap between slices.

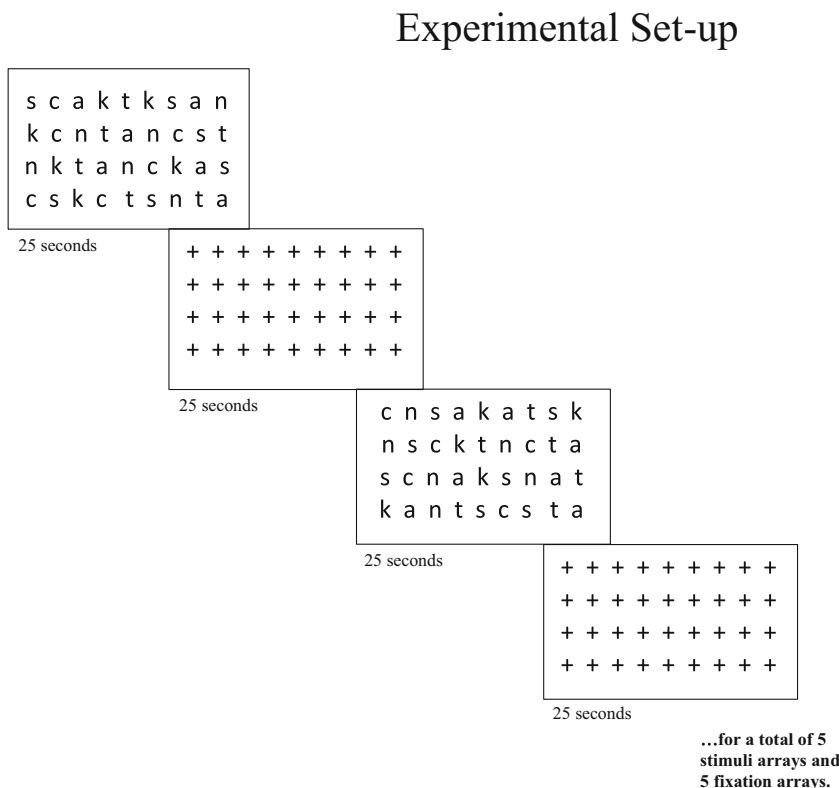
## Mean Activation Analysis

The first five image volumes were used to achieve a steady state of image contrast and were discarded prior to analysis. The remaining volumes were classified as task or fixation (rest) and were subject to standard pre-processing using SPM8 [38] which included realignment of images from all tasks to each other, slice timing correction within each task, co-registration between the functional and structural images, segmentation of the maps into the tissue probability maps representing gray matter, white matter and cerebrospinal fluid, normalization of the data into standard Montreal Neurological Imaging (MNI) space, and spatial smoothing using an 8-mm full width half maximum kernel. Data were then entered into a first level analysis using a block design and a general linear model approach with six motion parameters and response time as regressors (to remove the effect of time on task variance; [39]). The inclusion of the response time in the first level model also serves to partial out the potential differences between typical and atypical readers that is due to task difficulty (i.e., time taken to read through the matrices). In addition, the use of the fixation matrices as a baseline served to control for eye movement activity across all the tasks. Estimation of the hemodynamic response function (HRF) was completed using restricted maximum likelihood (ReML) estimation, and activation for each participant and for each task was thresholded at  $p < 0.001$  (no cluster-size correction). Mean activation maps for each group, for each task, as well as the between-group contrasts for each task, were created at an uncorrected  $p < 0.001$ , for descriptive purposes only. These maps are available as Supplementary Images 1–3.

## Regions of Interest Analysis

When considering whether to do a voxel-based (i.e., whole-cerebellum) approach vs. ROI approach, we evaluated (1) our research question and the extent of previous literature, and (2) the pros/cons of voxel-based approach vs. ROI-based approach.

**Fig. 2** An example of the stimulus and fixation arrays presented in the scanner



Ultimately, we felt that the ROI-based approach was the most appropriate for the following reasons. First, our research question is specifically focused on the role of the cerebellum in reading and there is enough previous literature to guide and support our selection of specific coordinates in the cerebellum that were associated with language vs. motor function (see below). Second, given the widespread involvement of the cerebellum across many tasks, a voxel-based approach could potentially obscure the reading-specific functions that we are interested in better understanding either through an overly conservative statistical correction given the number of voxels tested is greater than an ROI approach, and/or potentially spurious findings as per the exploratory nature of the voxel-based approach.

**ROI Selection** Based on a literature review of fMRI studies of reading- and language-related activity in the cerebellum, seven cerebellar regions of interest (ROIs) were selected for analysis according to their involvement in reading, speech/motor, or language tasks. Four ROIs were placed in areas of the cerebellum that have been linked to motor learning and/or speech motor control, and three ROIs were placed in areas of the cerebellum that have been previously identified as important for language tasks (see Fig. 3a and b). Each will be discussed in turn. Each ROI was a 6–10-mm sphere that was delineated on a standard anatomical template in MNI space using MANGO software [40]. The ROIs differed in size (6 or 10 mm) to best represent the anatomical structures and boundaries identified in previous work. For example, the cerebellar regions associated

with the caudate and putamen are very geographically close to one another and larger spheres would have overlapped. To ensure that we were not including the same voxels in multiple ROIs, we adjusted the spheres accordingly. Ultimately, the area included in motor ROIs was comparable to the area included in language ROIs (32 mm vs. 30 mm, respectively).

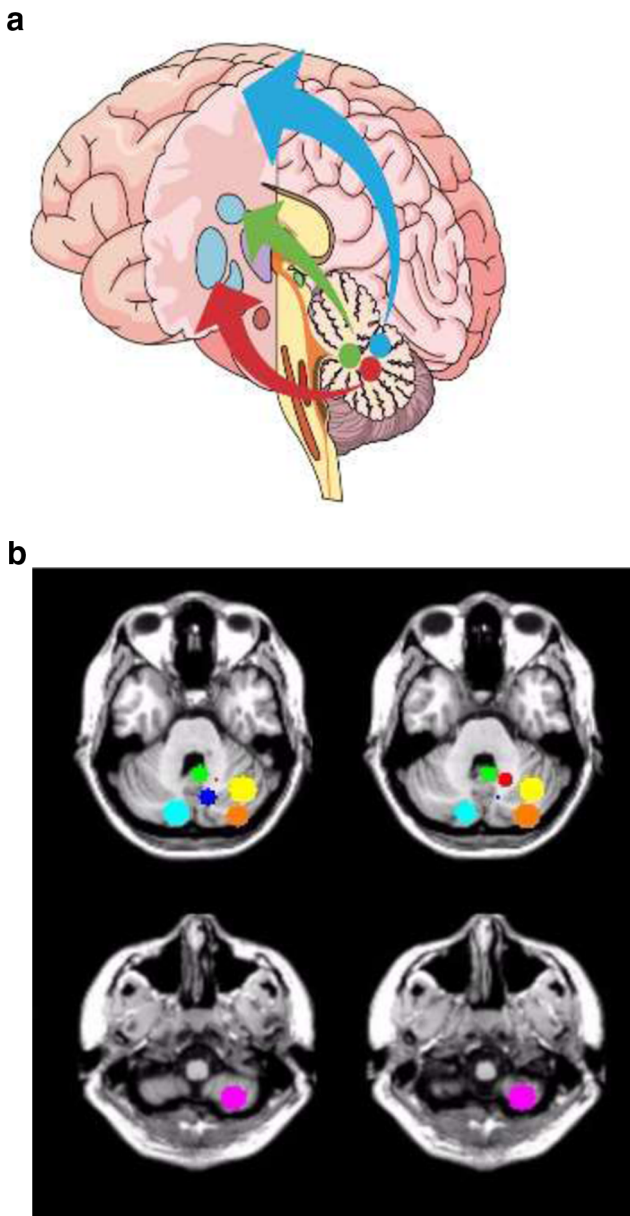
**Motor ROIs**

**ROI 1** A 6-mm sphere located on the right posterior lobe at  $x = 18$ ,  $y = -56$ , and  $z = -36$  (all coordinates in MNI space). This coordinate has been identified as a region of the cerebellum where the putamen is represented [41]. The putamen has been shown to play a role in motor output in both healthy (for a review see [42]) and clinical populations [43, 44].

**ROI 2** A 6-mm sphere located on the right anterior lobe at  $x = 6$ ,  $y = -52$ , and  $z = -30$ . This coordinate has been identified as a region of the cerebellum where the caudate nucleus is represented [41]. Bohland, Bullock, and Guenther [45] indicated that while the putamen is involved in the initiation of the actual motor command, the caudate plays a role in motor output by way of organization of phonemes into syllable bins.

**ROI 3** A 10-mm sphere located on the right posterior lobe of the cerebellum at  $x = 12$ ,  $y = -70$ , and  $z = -21$ . This ROI encompasses the putative “primary somatomotor” region [46], and the coordinates were calculated as the midway point between





**Fig. 3** **a** Somatotopic organization of the cerebellum. This illustrates connections between the putamen (red), caudate (green) and supplementary motor area (blue) and the cerebellar anterior, posterior, and vermal regions. **b** Location of cerebellar regions of interest. Red: ROI 1 (18, -56, -36); green: ROI 2 (6, -52, -30); blue: ROI 3 (12, -70, -21); pink: ROI 4 (27, -60, -60); aqua: ROI 5 (-12, -82, -26); yellow: ROI 6 (38, -64, -30); orange: ROI 7 (34, -83, -36)

adjacent cerebellar regions identified by O'Reilly et al. [46] as primary somatosensory and primary motor, respectively.

**ROI 4** A 10-mm sphere located on the right posterior lobe at  $x = 27$ ,  $y = -60$ , and  $z = -60$ . This ROI encompasses the “secondary somatomotor” region of the cerebellum and, in accordance with O'Reilly et al.'s [46] predictions, the coordinates were delineated as the midway point between adjacent secondary somatosensory and secondary motor areas.

## Language ROIs

**ROI 5** A 10-mm sphere located on the left posterior lobe of the cerebellum at  $x = -12$ ,  $y = -82$ , and  $z = -26$ . This cerebellar ROI has been linked to activity in the right DLPFC [47], which has been identified as an area of increased activation in adults with reading impairments [48].

**ROI 6** A 10-mm sphere located on the right posterior lobe at  $x = 38$ ,  $y = -64$ , and  $z = -30$ . This coordinate was identified as a primary area of peak cerebellar activation during reading tasks in a large-scale meta-analysis [49].

**ROI 7** A 10-mm sphere located on the right posterior lobe at  $x = 34$ ,  $y = -83$ , and  $z = -36$ . This coordinate was identified as a secondary area of peak cerebellar activation during reading tasks in a large-scale meta-analysis [49].

ROIs were individually imported into the MarsBar anatomy toolbox in SPM 8, and percent signal change (PSC; which represents the relative change in signal between task and baseline) (i.e., fixation matrices) for each ROI by task was extracted for every participant.

Data were entered into SPSS and mixed 2 (group)  $\times$  3 (task) ANOVAs were used to assess the interaction between the group and task, on PSC, for each ROI (i.e., the linear contrast effect for each interaction). Follow-up paired and independent samples  $t$  tests were used to follow up on significant interactions. Correction for multiple  $t$  test comparisons (i.e., our post hoc tests) was done using the Benjamini-Hochberg procedure [50],  $(i/m)Q$ , where  $i$  is the rank of an individual  $p$  value,  $m$  is the total number of comparisons, and  $Q$  is the false discovery rate (FDR), a value that is set a priori [50] and conventionally ranges between 10 and 20%.<sup>1</sup> FDR refers to the total number of results that incorrectly reject the null hypothesis (in other words, the number of false positive results), and is a powerful method for controlling type I error in analyses where a Bonferroni correction may be too stringent [51]. Using this correction assigns each  $p$  value a corresponding critical  $q$ -value, and results are considered significant when  $q < p$ , for that value and all others exceeding it in rank. The FDR for this correction was set at 10% in order to minimize and balance type I vs type II error. Critical values for each comparison for which significant results were obtained are provided in the tables.

<sup>1</sup> Setting FDR at 5% makes the multiple correction overly conservative. For example, according to MacDonald in <http://www.biostathandbook.com/multiplecomparisons.html>, “if the cost of additional experiments is low and the cost of a false negative (missing a potentially important discovery) is high, you should probably use a fairly high false discovery rate, like 0.10 or 0.20, so that you do not miss anything important. Sometimes people use a false discovery rate of 0.05, probably because of confusion about the difference between false discovery rate and probability of a false positive when the null is true; a false discovery rate of 0.05 is probably too low for many experiments.”

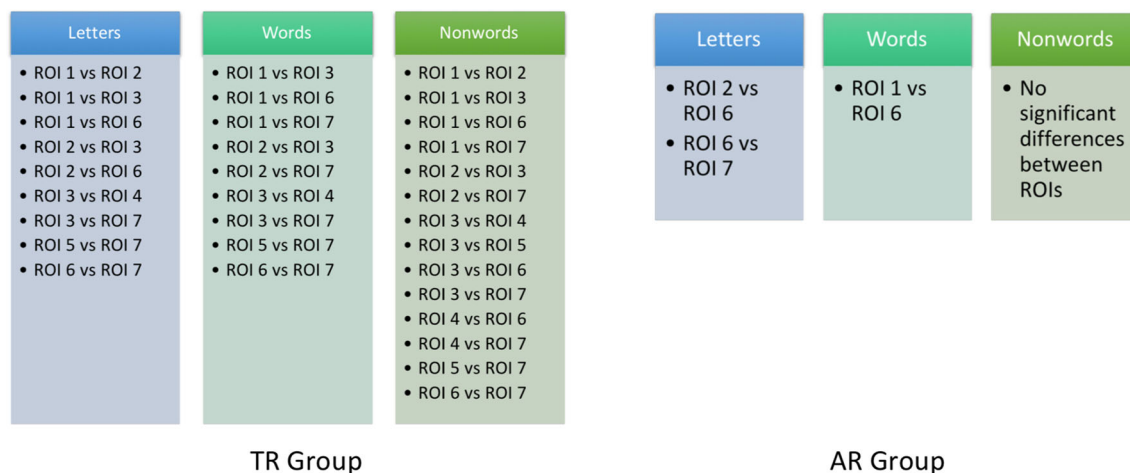
## Results

**Motor ROIs** There was a significant linear contrast interaction for ROI 1 ( $p = 0.013$ ), ROI 2 ( $p = 0.036$ ), and ROI 3 ( $p = 0.043$ ). The interaction was not significant for ROI 4 ( $p = 0.131$ ).

**Language ROIs** There was a significant linear contrast interaction for ROI 6 ( $p = 0.004$ ). All other ROI interactions were not significant (ROI 5,  $p = 0.894$ ; ROI 7,  $p = 0.817$ ).

**Task Specificity (Question One (Within Subjects))** Paired samples  $t$  tests for each ROI by task were performed on the TR and AR groups, separately. Overall, the TR group showed significant differences in activation intensity between ROIs for all tasks, particularly word and nonword reading, as depicted in Fig. 4. Individuals in the AR group showed no significant differences in activation intensity between ROIs for any of the rapid naming or reading tasks ( $t$ -values and critical values are reported in the [Appendix](#)).

**Group Specificity (Question Two (Between Subjects))** Independent samples  $t$  tests of PSC were performed for each of the three tasks per ROI. No significant between-group differences were found for any ROIs in the letter naming or nonword-reading conditions. For the word-reading condition, significant between-group differences in PSC were found in ROIs 1, 2, and 3 (all corresponding to motor processes), with  $p$  values of 0.025 (ROI 1), 0.027 (ROI 2), and 0.026 (ROI 3), respectively. These are illustrated in Fig. 5. Effect sizes were calculated using Cohen's  $d$  and were large ( $> 0.8$ ) for each significant result. Values for the word-reading condition are reported in Table 1 ( $t$ -values and critical values for all analyses are provided in the [Appendix](#)).



**Fig. 4** Task-specific activation in the cerebellum. This figure illustrates significant differences between cerebellar regions of interest (ROI) for three reading/rapid naming tasks in two groups of adults: those with typical (proficient) reading ability (TR group), and those with atypical

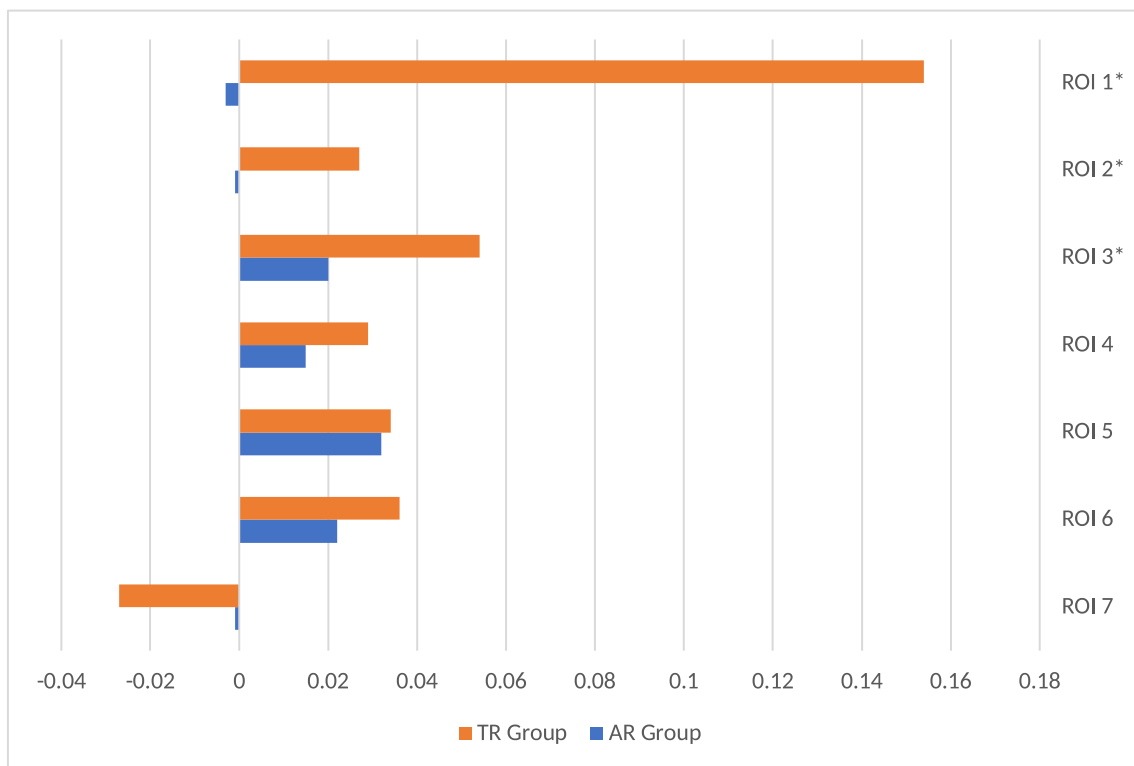
## Discussion

There is converging evidence that suggests that there are significant differences in cerebellar activation (as measured by fMRI) in individuals of typical and atypical reading proficiency (e.g., [12, 18]). Typically reading individuals tend to show activation in discrete regions of the cerebellum according to task demands (e.g., [23]), while less-proficient readers show more widespread activation throughout the cerebellar hemispheres during a range of reading tasks [18, 19, 30]. The present study confirms and extends current research on cerebellar contributions to reading by examining aspects of the reading process that are highly related to articulatory processing, i.e., silent reading of short, familiar words, and silent rapid naming of letters and through the isolation of specific cerebellar regions of interest based on their importance during language/reading or articulatory processing. We discuss the findings in the context of the two research questions, and how these results inform our understanding of typical and atypical reading processes.

*Do individuals who are atypical readers show decreased functional specialization for reading and rapid naming tasks in regions of the cerebellum associated with motor/articulatory and language processing, compared to typical readers?*

Yes. Typically reading adults were more likely to activate different regions of the cerebellum depending on whether they were being asked to name nonwords (reliance on language processing); name short, familiar words (reliance on language and articulatory processing); or name single letters (reliance on articulatory processing). While there may be individual differences with respect to reliance on the language and articulatory processing systems, and by no means are such processes independent, our findings do support the notion that there is a gradation of how these processes contribute to reading and rapid naming tasks that corresponds to the cerebellar ROIs (i.e., the

(less proficient) reading ability (AR group). Findings are reported at a corrected value  $FDR = 0.10$ . Values for all tests are reported in the [Appendix](#)



**Fig. 5** Between-group differences in brain activation (i.e., percent signal change) in each region of interest (ROI) for the word-reading condition. The box around ROIs 1–4 indicates regions associated with motor/articulatory processing. \*Significant at an adjusted value of  $p < 0.033$

rapid naming task showed specificity in the motor ROIs). In contrast, adults with RD showed no such differences or specificity of activation among the language or motor regions. That is, there was a comparable amount of activation in each of the ROIs, for each of the tasks, regardless of the language vs. motor distinctions, which is in line with previous fMRI studies [12, 19]. Here, we extend the previous literature by directly comparing tasks associated with motor/articulatory processing to those associated with language, in multiple ROIs that correspond to these same processes. And, importantly, we provide information on cerebellar activation during a rapid naming task, which had yet to be explicitly explored in reading literature.

While such findings are useful in providing a more comprehensive understanding of the neurobiological underpinnings characteristic of AR, we need to remember that reading operates at the level of a network and that the cerebellum is a single region within this network. As such, the extent to which reading difficulties arise because of (1) decreased activation in a cerebellar structure, (2) decreased activation in a structure that connects to the cerebellum (i.e., putamen), or (3) aberrant connections between the cerebellum and region in the cerebral cortex cannot be discerned from the current study. It is very likely that some combination of all three of these scenarios contributes to the complex processes involved in reading and the heterogeneous nature of reading impairments. What is clear from these results is that we need to consider regions beyond the cerebral cortex, including the cerebellum and

additional subcortical structures, to accurately and comprehensively advance models of reading and reading impairment.

*Are there differences in brain activation between individuals of typical and atypical reading proficiency during reading tasks and rapid naming tasks that vary in degree of motor/articulatory processing? In addition, if there are differences, do they manifest in cerebellar regions associated with motor/articulatory functions, language functions, or both?*

Yes. Individuals with AR were found to have significantly reduced activation in ROIs associated with motor processing during the word-reading condition. This finding underlines the importance of motor/articulatory contributions to reading performance, particularly for common and familiar words, which are processed in a highly automatized manner [52]. The importance of automaticity to reading performance cannot be overstated, particularly when reading is considered in the context of similar processes such as speech production, where proficiency is highly reliant on automaticity.

Recent evidence has been provided for a universal print-to-speech model that outlines how reading processes are built upon the framework of speech production [24, 52] and the findings here provide additional evidence for this notion. For example, the differences between typical readers and AR were only observed in ROIs associated with motor/articulatory functions and not in ROIs associated with language processing. However, there is compelling evidence that language regions of the cerebellum have a significant impact on reading



**Table 1** Between-group differences in percent signal change for the word-reading condition

Motor ROIs	Language ROIs
ROI 1: $t(30) = 2.354, p = 0.025^* q = 0.014$ <b>Cohen's <math>d = 0.859</math></b> Typical readers: ( $M = 0.154, SD = 0.226$ ) Atypical readers: ( $M = -0.003, SD = 0.020$ )	ROI 5: $t(29) = 0.126, p = 0.90$ Typical readers: ( $M = 0.034, SD = 0.048$ ) Atypical readers: ( $M = 0.032, SD = 0.046$ )
ROI 2: $t(29) = 2.334, p = 0.027^* q = 0.043$ <b>Cohen's <math>d = 0.866</math></b> Typical readers: ( $M = 0.027, SD = 0.034$ ) Atypical readers: ( $M = -0.001, SD = 0.030$ )	ROI 6: $t(29) = 1.235, p = 0.227$ Typical readers: ( $M = 0.036, SD = 0.032$ ) Atypical readers: ( $M = 0.022, SD = 0.028$ )
ROI 3: $t(30) = 2.341, p = 0.026^* q = 0.029$ <b>Cohen's <math>d = 0.854</math></b> Typical readers: ( $M = 0.054, SD = 0.046$ ) Atypical readers: ( $M = 0.020, SD = 0.030$ )	ROI 7: $t(29) = -1.382, p = 0.177$ Typical readers: ( $M = -0.027, SD = 0.041$ ) Atypical readers: ( $M = -0.001, SD = 0.061$ )
ROI 4: $t(29) = 0.984, p = 0.333$ Typical readers: ( $M = 0.029, SD = 0.046$ ) Atypical readers: ( $M = 0.015, SD = 0.025$ )	

\*Significant at FDR 0.10 (critical values alongside  $p$  values)

performance, and the present findings do not refute this. Instead, it is most likely that the widespread, whole-brain differences in neural architecture and function that differentiate individuals of typical and atypical reading proficiency are manifested throughout the cerebellum, and that the impact of such differences extends to difficulties both with motor/articulatory processing, and language (semantic, syntactic) processing, both of which contribute to poor reading performance. These findings fit with the current literature on the double-deficit hypothesis [53], which suggests that motor/articulatory processing efficiency (as indicated by RAN speed) is an important contributor to reading proficiency in adults, alongside phonological deficits [48, 53]. Our findings indicate that the cerebellum is one potential region from where such behavioral difficulties may result and provide support for future investigations into other subcortical structures that are likely contributors to problems with reading automaticity and efficiency.

### Limitations and Considerations for Future Research

From a methodological perspective, there are several approaches that can be taken to delineate ROIs. Here we used a whole-brain masking technique, whereby the subject's brains are warped to fit a predefined anatomical atlas. This allows for standardization of coordinates in MNI space. Alternative techniques include the use of SUIT, which is sensitive to individual variability and thus allows for more variability in anatomy [54] and subject-by-subject ROI delineation (i.e., by hand). The advantages and drawbacks to each technique are numerous and beyond the scope of the current work. What is important to consider in future work is whether the anatomical/functional composition of the cerebellum, and

subsequent analysis of brain activity, is impacted substantially by the choice of ROI methodology. Given that the cerebellum is becoming a noteworthy region in language literature, future research that explores the application of each of these approaches to the study of the cerebellum would be useful.

Additionally, we included left-handed participants in our analysis. There is a possibility that some individuals in our study could display abnormal lateralization patterns for language, which would affect patterns of activation in the ROIs. Approximately 5% of right-handers and 15% of left-handers deviate from the expected left-hemispheric lateralization for language in the cerebral cortex (see [55]). However, while the cerebellum displays a similar (but reversed) tendency to lateralize language functions to one hemisphere, evidence from brain imaging studies suggests that both right- and left-handers tend to localize language functions to the right hemisphere of the cerebellum, regardless of lateralization patterns in the cerebral cortex [55]. For this reason, it is unlikely that excluding data from the five left-handed individuals included in our study would affect the outcomes we have presented here, but ultimately work that explores lateralization of the cerebellum in typical and atypical readers would be needed to fully test this claim.

### Conclusions

Reading requires highly coordinated and precise processing within and between regional neural networks associated with print, sound, and articulation. The cerebellum is a sub-cortical structure noted for its role in coordinated processing, generally, and motor coordination, specifically. While the cerebellum differentially

responds to language and motor tasks, how it responds to tasks that include both motor/articulatory and language components (such as rapid reading/naming) has not previously been explored. Here, we demonstrated that adults with atypical reading proficiency were less likely to demonstrate functional specialization within the cerebellum during silent reading and naming tasks, compared to skilled readers. This finding was stable across three tasks (silent nonword reading, silent word reading, silent naming of letters) that required various levels of language and motor/articulatory processing. We also found that areas of difference between typical and atyp-

ical readers were found only in cerebellar regions related to motor/articulatory processing. These results lend support to current research that indicates that silent word reading is inextricably linked to articulatory processes, and suggests that it may be neither useful nor accurate to continue to emphasize a strict dichotomy between reading and speech production.

### Compliance with Ethical Standards

**Conflict of Interest** The authors declare that they have no conflicts of interest.

## Appendix

**Table 2** Paired samples test (TR group, words condition)

		Paired differences				<i>t</i>	df	Sig. (2-tailed)
		Mean	Std. deviation	Std. error mean	95% confidence interval of the difference			
					Lower	Upper		
Pair 1	Words ROI 1–words ROI 2	−0.013176	0.024633	0.005974	−0.025842	−0.000511	−2.206	16 0.042
Pair 2	Words ROI 1–words ROI 3	−0.038222	0.039760	0.009372	−0.057995	−0.018450	−4.079	17 0.001
Pair 3	Words ROI 1–words ROI 4	−0.013222	0.035431	0.008351	−0.030842	0.004397	−1.583	17 0.132
Pair 4	Words ROI 1–words ROI 5	−0.020824	0.044386	0.010765	−0.043645	0.001998	−1.934	16 0.071
Pair 5	Words ROI 1–words ROI 6	−0.020556	0.026615	0.006273	−0.033791	−0.007320	−3.277	17 0.004
Pair 6	Words ROI 1–words ROI 7	0.042111	0.039213	0.009243	0.022611	0.061611	4.556	17 0.000
Pair 7	Words ROI 2–words ROI 3	−0.022353	0.028786	0.006982	−0.037153	−0.007553	−3.202	16 0.006
Pair 8	Words ROI 2–words ROI 4	0.001824	0.030194	0.007323	−0.013701	0.017348	0.249	16 0.807
Pair 9	Words ROI 2–words ROI 5	−0.009688	0.042417	0.010604	−0.032290	0.012915	−0.914	15 0.375
Pair 10	Words ROI 2–words ROI 6	−0.005882	0.030539	0.007407	−0.021584	0.009819	−0.794	16 0.439
Pair 11	Words ROI 2–words ROI 7	0.055412	0.050152	0.012164	0.029626	0.081198	4.555	16 0.000
Pair 12	Words ROI 3–words ROI 4	0.025000	0.043029	0.010142	0.003602	0.046398	2.465	17 0.025
Pair 13	Words ROI 3–words ROI 5	0.020176	0.043428	0.010533	−0.002152	0.042505	1.916	16 0.073
Pair 14	Words ROI 3–words ROI 6	0.017667	0.034009	0.008016	0.000755	0.034579	2.204	17 0.042
Pair 15	Words ROI 3–words ROI 7	0.080333	0.049866	0.011753	0.055536	0.105131	6.835	17 0.000
Pair 16	Words ROI 4–words ROI 5	−0.011353	0.049999	0.012126	−0.037060	0.014354	−0.936	16 0.363
Pair 17	Words ROI 4–words ROI 6	−0.007333	0.027585	0.006502	−0.021051	0.006384	−1.128	17 0.275
Pair 18	Words ROI 4–words ROI 7	0.055333	0.055201	0.013011	0.027882	0.082784	4.253	17 0.001
Pair 19	Words ROI 5–words ROI 6	0.000765	0.041241	0.010002	−0.020439	0.021969	0.076	16 0.940
Pair 20	Words ROI 5–words ROI 7	0.058471	0.048764	0.011827	0.033399	0.083543	4.944	16 0.000
Pair 21	Words ROI 6–words ROI 7	0.062667	0.039111	0.009218	0.043217	0.082116	6.798	17 0.000

**Table 3** Paired samples test (AR group, words condition)

		Paired differences					<i>t</i>	df	Sig. (2-tailed)
		Mean	Std. deviation	Std. error mean	95% confidence interval of the difference				
					Lower	Upper			
Pair 1	Words ROI 1–words ROI 2	-0.002429	0.021209	0.005668	-0.014674	0.009817	-0.428	13	0.675
Pair 2	Words ROI 1–words ROI 3	-0.022929	0.034658	0.009263	-0.042939	-0.002918	-2.475	13	0.028
Pair 3	Words ROI 1–words ROI 4	-0.016154	0.028222	0.007827	-0.033208	0.000900	-2.064	12	0.061
Pair 4	Words ROI 1–words ROI 5	-0.034357	0.044863	0.011990	-0.060260	-0.008454	-2.865	13	0.013
Pair 5	Words ROI 1–words ROI 6	-0.025923	0.022976	0.006372	-0.039808	-0.012039	-4.068	12	0.002
Pair 6	Words ROI 1–words ROI 7	0.000077	0.054249	0.015046	-0.032705	0.032859	0.005	12	0.996
Pair 7	Words ROI 2–words ROI 3	-0.020500	0.037270	0.009961	-0.042019	0.001019	-2.058	13	0.060
Pair 8	Words ROI 2–words ROI 4	-0.014000	0.030846	0.008555	-0.032640	0.004640	-1.636	12	0.128
Pair 9	Words ROI 2–words ROI 5	-0.031929	0.049180	0.013144	-0.060324	-0.003533	-2.429	13	0.030
Pair 10	Words ROI 2–words ROI 6	-0.020385	0.030626	0.008494	-0.038891	-0.001878	-2.400	12	0.034
Pair 11	Words ROI 2–words ROI 7	0.002231	0.063003	0.017474	-0.035841	0.040303	0.128	12	0.901
Pair 12	Words ROI 3–words ROI 4	0.006231	0.024101	0.006684	-0.008333	0.020795	0.932	12	0.370
Pair 13	Words ROI 3–words ROI 5	-0.011429	0.040327	0.010778	-0.034713	0.011856	-1.060	13	0.308
Pair 14	Words ROI 3–words ROI 6	0.002385	0.023397	0.006489	-0.011754	0.016523	0.367	12	0.720
Pair 15	Words ROI 3–words ROI 7	0.022462	0.064529	0.017897	-0.016533	0.061456	1.255	12	0.233
Pair 16	Words ROI 4–words ROI 5	-0.017692	0.049211	0.013649	-0.047430	0.012046	-1.296	12	0.219
Pair 17	Words ROI 4–words ROI 6	-0.002333	0.023868	0.006890	-0.017499	0.012832	-0.339	11	0.741
Pair 18	Words ROI 4–words ROI 7	0.016231	0.065196	0.018082	-0.023167	0.055628	0.898	12	0.387
Pair 19	Words ROI 5–words ROI 6	0.011769	0.034211	0.009488	-0.008904	0.032442	1.240	12	0.239
Pair 20	Words ROI 5–words ROI 7	0.033923	0.057040	0.015820	-0.000546	0.068392	2.144	12	0.053
Pair 21	Words ROI 6–words ROI 7	0.028250	0.044902	0.012962	-0.000279	0.056779	2.179	11	0.052

**Table 4** Paired samples test (TR group, letters condition)

		Paired differences					<i>t</i>	df	Sig. (2-tailed)
		Mean	Std. deviation	Std. error mean	95% confidence interval of the difference				
					Lower	Upper			
Pair 1	Letters ROI 1–letters ROI 2	-0.012529	0.019596	0.004753	-0.022605	-0.002454	-2.636	16	0.018
Pair 2	Letters ROI 1–letters ROI 3	-0.036118	0.036052	0.008744	-0.054654	-0.017582	-4.131	16	0.001
Pair 3	Letters ROI 1–letters ROI 4	-0.009412	0.035593	0.008633	-0.027712	0.008889	-1.090	16	0.292
Pair 4	Letters ROI 1–letters ROI 5	-0.024941	0.052515	0.012737	-0.051942	0.002059	-1.958	16	0.068
Pair 5	Letters ROI 1–letters ROI 6	-0.030347	0.025856	0.006271	-0.043641	-0.017053	-4.839	16	0.000
Pair 6	Letters ROI 1–letters ROI 7	0.011412	0.040702	0.009872	-0.009515	0.032339	1.156	16	0.265
Pair 7	Letters ROI 2–letters ROI 3	-0.023588	0.038378	0.009308	-0.043320	-0.003856	-2.534	16	0.022
Pair 8	Letters ROI 2–letters ROI 4	0.003118	0.036059	0.008746	-0.015422	0.021657	0.356	16	0.726
Pair 9	Letters ROI 2–letters ROI 5	-0.012412	0.058931	0.014293	-0.042711	0.017888	-0.868	16	0.398
Pair 10	Letters ROI 2–letters ROI 6	-0.017818	0.028611	0.006939	-0.032528	-0.003107	-2.568	16	0.021
Pair 11	Letters ROI 2–letters ROI 7	0.023941	0.047527	0.011527	-0.000495	0.048377	2.077	16	0.054
Pair 12	Letters ROI 3–letters ROI 4	0.026706	0.045842	0.011118	0.003136	0.050276	2.402	16	0.029

**Table 4** (continued)

		Paired differences					<i>t</i>	df	Sig. (2-tailed)
		Mean	Std. deviation	Std. error mean	95% confidence interval of the difference				
					Lower	Upper			
Pair 13	Letters ROI 3–letters ROI 5	0.011176	0.047708	0.011571	−0.013353	0.035706	0.966	16	0.348
Pair 14	Letters ROI 3–letters ROI 6	0.005771	0.028617	0.006941	−0.008943	0.020484	0.831	16	0.418
Pair 15	Letters ROI 3–letters ROI 7	0.047529	0.058008	0.014069	0.017705	0.077354	3.378	16	0.004
Pair 16	Letters ROI 4–letters ROI 5	−0.015529	0.047301	0.011472	−0.039849	0.008791	−1.354	16	0.195
Pair 17	Letters ROI 4–letters ROI 6	−0.020935	0.032938	0.007989	−0.037870	−0.004000	−2.621	16	0.019
Pair 18	Letters ROI 4–letters ROI 7	0.021222	0.061952	0.014602	−0.009586	0.052030	1.453	17	0.164
Pair 19	Letters ROI 5–letters ROI 6	−0.005406	0.050465	0.012240	−0.031353	0.020541	−0.442	16	0.665
Pair 20	Letters ROI 5–letters ROI 7	0.036353	0.066182	0.016052	0.002325	0.070381	2.265	16	0.038
Pair 21	Letters ROI 6–letters ROI 7	0.041759	0.052273	0.012678	0.014883	0.068635	3.294	16	0.005

**Table 5** Paired samples test (AR group, letters condition)

		Paired differences					<i>t</i>	df	Sig. (2-tailed)
		Mean	Std. deviation	Std. error mean	95% confidence interval of the difference				
					Lower	Upper			
Pair 1	Letters ROI 1–letters ROI 2	−0.004154	0.024549	0.006809	−0.018989	0.010681	−0.610	12	0.553
Pair 2	Letters ROI 1–letters ROI 3	−0.015846	0.029950	0.008307	−0.033944	0.002252	−1.908	12	0.081
Pair 3	Letters ROI 1–letters ROI 4	−0.013077	0.023747	0.006586	−0.027427	0.001273	−1.986	12	0.070
Pair 4	Letters ROI 1–letters ROI 5	−0.013846	0.044632	0.012379	−0.040817	0.013124	−1.119	12	0.285
Pair 5	Letters ROI 1–letters ROI 6	−0.029923	0.039464	0.010945	−0.053771	−0.006075	−2.734	12	0.018
Pair 6	Letters ROI 1–letters ROI 7	0.007308	0.066266	0.018379	−0.032737	0.047352	0.398	12	0.698
Pair 7	Letters ROI 2–letters ROI 3	−0.011143	0.035248	0.009420	−0.031495	0.009209	−1.183	13	0.258
Pair 8	Letters ROI 2–letters ROI 4	−0.008923	0.027409	0.007602	−0.025486	0.007640	−1.174	12	0.263
Pair 9	Letters ROI 2–letters ROI 5	−0.011500	0.050360	0.013459	−0.040577	0.017577	−0.854	13	0.408
Pair 10	Letters ROI 2–letters ROI 6	−0.030143	0.034552	0.009234	−0.050092	−0.010193	−3.264	13	0.006
Pair 11	Letters ROI 2–letters ROI 7	0.011462	0.052301	0.014506	−0.020144	0.043067	0.790	12	0.445
Pair 12	Letters ROI 3–letters ROI 4	0.002769	0.031343	0.008693	−0.016171	0.021709	0.319	12	0.756
Pair 13	Letters ROI 3–letters ROI 5	−0.000357	0.039199	0.010476	−0.022990	0.022276	−0.034	13	0.973
Pair 14	Letters ROI 3–letters ROI 6	−0.019000	0.031650	0.008459	−0.037274	−0.000726	−2.246	13	0.043
Pair 15	Letters ROI 3–letters ROI 7	0.023154	0.060498	0.016779	−0.013405	0.059712	1.380	12	0.193
Pair 16	Letters ROI 4–letters ROI 5	−0.000769	0.047339	0.013130	−0.029376	0.027838	−0.059	12	0.954
Pair 17	Letters ROI 4–letters ROI 6	−0.016846	0.038096	0.010566	−0.039867	0.006175	−1.594	12	0.137
Pair 18	Letters ROI 4–letters ROI 7	0.020385	0.062256	0.017267	−0.017236	0.058005	1.181	12	0.261
Pair 19	Letters ROI 5–letters ROI 6	−0.018643	0.042774	0.011432	−0.043340	0.006054	−1.631	13	0.127
Pair 20	Letters ROI 5–letters ROI 7	0.021154	0.060889	0.016888	−0.015641	0.057949	1.253	12	0.234
Pair 21	Letters ROI 6–letters ROI 7	0.037231	0.041330	0.011463	0.012255	0.062206	3.248	12	0.007



**Table 6** Paired samples test (TR group, nonwords condition)

		Paired differences				<i>t</i>	df	Sig. (2-tailed)	
		Mean	Std. deviation	Std. error mean	95% confidence interval of the difference				
					Lower				Upper
Pair 1	Nonwords ROI 1–nonwords ROI 2	–0.011882	0.024199	0.005869	–0.024325	0.000560	–2.025	16	0.060
Pair 2	Nonwords ROI 1–nonwords ROI 3	–0.054529	0.044713	0.010845	–0.077519	–0.031540	–5.028	16	0.000
Pair 3	Nonwords ROI 1–nonwords ROI 4	–0.007765	0.031164	0.007558	–0.023788	0.008258	–1.027	16	0.320
Pair 4	Nonwords ROI 1–nonwords ROI 5	–0.016294	0.044463	0.010784	–0.039155	0.006567	–1.511	16	0.150
Pair 5	Nonwords ROI 1–nonwords ROI 6	–0.030765	0.034752	0.008429	–0.048632	–0.012897	–3.650	16	0.002
Pair 6	Nonwords ROI 1–nonwords ROI 7	0.025588	0.043004	0.010430	0.003477	0.047699	2.453	16	0.026
Pair 7	Nonwords ROI 2–nonwords ROI 3	–0.042647	0.052883	0.012826	–0.069837	–0.015457	–3.325	16	0.004
Pair 8	Nonwords ROI 2–nonwords ROI 4	0.004118	0.041692	0.010112	–0.017318	0.025554	0.407	16	0.689
Pair 9	Nonwords ROI 2–nonwords ROI 5	–0.004412	0.053260	0.012917	–0.031796	0.022972	–0.342	16	0.737
Pair 10	Nonwords ROI 2–nonwords ROI 6	–0.018882	0.047123	0.011429	–0.043111	0.005346	–1.652	16	0.118
Pair 11	Nonwords ROI 2–nonwords ROI 7	0.037471	0.053078	0.012873	0.010180	0.064761	2.911	16	0.010
Pair 12	Nonwords ROI 3–nonwords ROI 4	0.046765	0.036881	0.008945	0.027802	0.065727	5.228	16	0.000
Pair 13	Nonwords ROI 3–nonwords ROI 5	0.038235	0.048888	0.011857	0.013099	0.063371	3.225	16	0.005
Pair 14	Nonwords ROI 3–nonwords ROI 6	0.023765	0.037666	0.009135	0.004399	0.043131	2.601	16	0.019
Pair 15	Nonwords ROI 3–nonwords ROI 7	0.071778	0.064634	0.015234	0.039636	0.103920	4.712	17	0.000
Pair 16	Nonwords ROI 4–nonwords ROI 5	–0.008529	0.040623	0.009853	–0.029416	0.012357	–0.866	16	0.399
Pair 17	Nonwords ROI 4–nonwords ROI 6	–0.023000	0.030430	0.007380	–0.038646	–0.007354	–3.116	16	0.007
Pair 18	Nonwords ROI 4–nonwords ROI 7	0.033353	0.049104	0.011910	0.008106	0.058600	2.801	16	0.013
Pair 19	Nonwords ROI 5–nonwords ROI 6	–0.014471	0.029381	0.007126	–0.029577	0.000636	–2.031	16	0.059
Pair 20	Nonwords ROI 5–nonwords ROI 7	0.041882	0.028313	0.006867	0.027325	0.056439	6.099	16	0.000
Pair 21	Nonwords ROI 6–nonwords ROI 7	0.056353	0.040611	0.009850	0.035473	0.077233	5.721	16	0.000

**Table 7** Paired samples test (AR group, nonwords condition)

		Paired differences				<i>t</i>	df	Sig. (2-tailed)	
		Mean	Std. deviation	Std. error mean	95% confidence interval of the difference				
					Lower				Upper
Pair 1	Nonwords ROI 1–nonwords ROI 2	0.001143	0.020979	0.005607	–0.010970	0.013256	0.204	13	0.842
Pair 2	Nonwords ROI 1–nonwords ROI 3	–0.009714	0.037308	0.009971	–0.031255	0.011827	–0.974	13	0.348
Pair 3	Nonwords ROI 1–nonwords ROI 4	–0.004462	0.042604	0.011816	–0.030207	0.021284	–0.378	12	0.712
Pair 4	Nonwords ROI 1–nonwords ROI 5	0.007071	0.054705	0.014621	–0.024515	0.038657	0.484	13	0.637
Pair 5	Nonwords ROI 1–nonwords ROI 6	–0.005357	0.047111	0.012591	–0.032558	0.021844	–0.425	13	0.677
Pair 6	Nonwords ROI 1–nonwords ROI 7	0.037538	0.074323	0.020614	–0.007375	0.082452	1.821	12	0.094
Pair 7	Nonwords ROI 2–nonwords ROI 3	–0.010857	0.031971	0.008545	–0.029317	0.007602	–1.271	13	0.226
Pair 8	Nonwords ROI 2–nonwords ROI 4	–0.003154	0.041964	0.011639	–0.028512	0.022205	–0.271	12	0.791
Pair 9	Nonwords ROI 2–nonwords ROI 5	0.005929	0.044391	0.011864	–0.019702	0.031559	0.500	13	0.626
Pair 10	Nonwords ROI 2–nonwords ROI 6	–0.006500	0.041100	0.010984	–0.030230	0.017230	–0.592	13	0.564
Pair 11	Nonwords ROI 2–nonwords ROI 7	0.038846	0.073483	0.020381	–0.005559	0.083252	1.906	12	0.081

**Table 7** (continued)

		Paired differences				<i>t</i>	df	Sig. (2-tailed)
		Mean	Std. deviation	Std. error mean	95% confidence interval of the difference			
					Lower	Upper		
Pair 12	Nonwords ROI 3–nonwords ROI 4	0.008000	0.027289	0.007568	–0.008490	0.024490	1.057	12 0.311
Pair 13	Nonwords ROI 3–nonwords ROI 5	0.016786	0.037012	0.009892	–0.004584	0.038156	1.697	13 0.114
Pair 14	Nonwords ROI 3–nonwords ROI 6	0.004357	0.027219	0.007275	–0.011359	0.020073	0.599	13 0.559
Pair 15	Nonwords ROI 3–nonwords ROI 7	0.050000	0.058737	0.016291	0.014506	0.085494	3.069	12 0.010
Pair 16	Nonwords ROI 4–nonwords ROI 5	0.003000	0.048712	0.013510	–0.026436	0.032436	0.222	12 0.828
Pair 17	Nonwords ROI 4–nonwords ROI 6	–0.008692	0.031816	0.008824	–0.027918	0.010534	–0.985	12 0.344
Pair 18	Nonwords ROI 4–nonwords ROI 7	0.042000	0.061226	0.016981	0.005001	0.078999	2.473	12 0.029
Pair 19	Nonwords ROI 5–nonwords ROI 6	–0.012429	0.039130	0.010458	–0.035022	0.010165	–1.188	13 0.256
Pair 20	Nonwords ROI 5–nonwords ROI 7	0.039000	0.085091	0.023600	–0.012420	0.090420	1.653	12 0.124
Pair 21	Nonwords ROI 6–nonwords ROI 7	0.050692	0.054333	0.015069	0.017859	0.083525	3.364	12 0.006

**Table 8** Independent samples test (letters condition)

<i>t</i> test for equality of means							
	<i>t</i>	df	Sig. (2-tailed)	Mean difference	Std. error difference	95% confidence interval of the difference	
						Lower	Upper
Letters ROI 1	–1.532	28	0.137	–0.009941	0.006487	–0.023230	0.003348
Letters ROI 2	–0.164	29	0.871	–0.001626	0.009938	–0.021952	0.018700
Letters ROI 3	0.797	29	0.432	0.010819	0.013579	–0.016953	0.038592
Letters ROI 4	–1.516	29	0.140	–0.018966	0.012514	–0.044559	0.006628
Letters ROI 5	–0.040	29	0.968	–0.000714	0.017689	–0.036893	0.035464
Letters ROI 6	–1.036	29	0.309	–0.013951	0.013464	–0.041489	0.013586
Letters ROI 7	–0.999	29	0.326	–0.019803	0.019830	–0.060360	0.020753

**Table 9** Group statistics (letters condition)

	Group	<i>N</i>	Mean	Std. deviation	Std. error mean
Letters ROI 1	TR	17	0.00906	0.019980	0.004846
	AR	13	0.01900	0.013826	0.003835
Letters ROI 2	TR	17	0.02159	0.031030	0.007526
	AR	14	0.02321	0.022505	0.006015
Letters ROI 3	TR	17	0.04518	0.041330	0.010024
	AR	14	0.03436	0.032490	0.008683
Letters ROI 4	TR	18	0.01311	0.042766	0.010080
	AR	13	0.03208	0.016297	0.004520
Letters ROI 5	TR	17	0.03400	0.052961	0.012845
	AR	14	0.03471	0.043667	0.011671
Letters ROI 6	TR	17	0.03941	0.034730	0.008423
	AR	14	0.05336	0.040252	0.010758
Letters ROI 7	TR	18	–0.00811	0.048588	0.011452
	AR	13	0.01169	0.061877	0.017162

**Table 10** Independent samples test (nonwords condition)

	<i>t</i> test for equality of means						
	<i>t</i>	df	Sig. (2-tailed)	Mean difference	Std. error difference	95% confidence interval of the difference	
						Lower	Upper
Nonwords ROI 1	−0.229	29	0.821	−0.002084	0.009105	−0.020705	0.016537
Nonwords ROI 2	0.915	29	0.368	0.010941	0.011961	−0.013521	0.035403
Nonwords ROI 3	1.652	30	0.109	0.030976	0.018752	−0.007321	0.069274
Nonwords ROI 4	0.124	28	0.902	0.001439	0.011563	−0.022247	0.025125
Nonwords ROI 5	1.121	29	0.271	0.021282	0.018983	−0.017543	0.060107
Nonwords ROI 6	1.596	29	0.121	0.023324	0.014618	−0.006573	0.053220
Nonwords ROI 7	0.336	29	0.739	0.006671	0.019854	−0.033934	0.047276

**Table 11** Group statistics (nonwords condition)

	Group	<i>N</i>	Mean	Std. deviation	Std. error mean
Nonwords ROI 1	TR	17	0.00806	0.015590	0.003781
	AR	14	0.01014	0.033475	0.008947
Nonwords ROI 2	TR	17	0.01994	0.027289	0.006619
	AR	14	0.00900	0.039160	0.010466
Nonwords ROI 3	TR	18	0.05083	0.065821	0.015514
	AR	14	0.01986	0.026930	0.007197
Nonwords ROI 4	TR	17	0.01582	0.034262	0.008310
	AR	13	0.01438	0.027076	0.007509
Nonwords ROI 5	TR	17	0.02435	0.049655	0.012043
	AR	14	0.00307	0.056010	0.014969
Nonwords ROI 6	TR	17	0.03882	0.037690	0.009141
	AR	14	0.01550	0.043717	0.011684
Nonwords ROI 7	TR	18	−0.02094	0.048798	0.011502
	AR	13	−0.02762	0.061781	0.017135

**Table 12** Independent samples test (words condition)

	<i>t</i> test for equality of means						
	<i>t</i>	df	Sig. (2-tailed)	Mean difference	Std. error difference	95% confidence interval of the difference	
						Lower	Upper
Words ROI 1	2.354	30	0.025	0.017944	0.007622	0.002378	0.033511
Words ROI 2	2.334	29	0.027	0.027189	0.011649	0.003365	0.051013
Words ROI 3	2.341	30	0.026	0.033238	0.014196	0.004246	0.062230
Words ROI 4	1.076	27.408	0.291	0.013897	0.012918	−0.012591	0.040385
Words ROI 5	0.126	29	0.900	0.002143	0.016971	−0.032566	0.036852
Words ROI 6	1.235	29	0.227	0.013615	0.011028	−0.008940	0.036171
Words ROI 7	−1.382	29	0.177	−0.025205	0.018236	−0.062501	0.012091

**Table 13** Group statistics (words condition)

	Group	<i>N</i>	Mean	Std. deviation	Std. error mean
Words ROI 1	TR	18	0.01544	0.022566	0.005319
	AR	14	-0.00250	0.019747	0.005278
Words ROI 2	TR	17	0.02712	0.033959	0.008236
	AR	14	-0.00007	0.030075	0.008038
Words ROI 3	TR	18	0.05367	0.045889	0.010816
	AR	14	0.02043	0.030143	0.008056
Words ROI 4	TR	18	0.02867	0.046017	0.010846
	AR	13	0.01477	0.025302	0.007018
Words ROI 5	TR	17	0.03400	0.047779	0.011588
	AR	14	0.03186	0.046073	0.012314
Words ROI 6	TR	18	0.03600	0.032145	0.007577
	AR	13	0.02238	0.027473	0.007620
Words ROI 7	TR	18	-0.02667	0.040961	0.009654
	AR	13	-0.00146	0.060739	0.016846

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